# Science case for UVSat space mission
## (version with double telescope for UV & visual photometry)

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## 1. Introduction

This document defines the scientific objectives of the satellite design with the working name UVSat, which will be used **to study the photometric variability of relatively bright objects in the near ultraviolet (UV)** and visible domains. In order to define these goals, the importance of UV observations is crucial; simultaneous observations in the visual will play an auxiliary role. In determining the scientific objectives of the project, the following general assumptions are adopted:

- The satellite will host two coupled telescopes, one with optics adapted for broadband observations in the satellite ultraviolet (long-wavelength part of the Balmer continuum, 200 – 300 nm), the other – for observation in the visible range (500 – 600 nm).
- The field of view of both telescopes should be similar and of the order of 10° × 10°.
- The satellite will be placed on a low-Earth solar-synchronous polar orbit.
- Observations of a given field will be conducted continuously for a period of 1 to 6 months.

## 2. Variability studies in UV

Choosing the UV range means that the observation will be focused on hot objects. On the one hand, it means young stars, and on the other – stars in the final phases of evolution. In the next chapter, we point to those objects for which observations of variability in UV, in combination with simultaneous observations in the visible domain, can bring important scientific results. At the end of this document these objects were ranked according to the subjective assessment of the significance of the proposed studies, which observations with UVSat can bring, made by the authors of this study.

The last two decades in observational astronomy can be called the time of sky surveys, conducted both from the ground and space. This is associated not only with a very rapid progress in the construction of telescopes. Observational astronomy more and more often uses the possibilities offered by modern detectors to study the variability of objects. This change of approach is defined as **time-domain astronomy**. The variability adds a completely new dimension to typical measurements based mainly on photometry and spectroscopy: time. For the variability study, important is not only the distribution of observations in time – which defines the time scales to be measured – but also the wavelength range in which the observations are carried out. Ground-based projects are limited to visual or near infrared but the space photometric surveys were also mostly carried out in a wide band (or bands) in the visual domain (Hipparcos, MOST, CoRoT, Kepler, BRITE-Constellation, Gaia, now TESS).

Ultraviolet – apart from the wavelength range available from Earth (320 nm < λ < 400 nm) – is a domain in which very few observations focused on the variability study have been conducted so far. Much more common are reviews in which observations of a given source are made not more than several times (e.g. GALEX). Ultraviolet is a spectral region in which the hot objects radiate strongly.

This is therefore a key domain for research on both very young and massive objects (OB stars, Wolf-Rayet stars, LBV stars), as well as stars in the final stages of evolution (white dwarfs, hot subdwarfs). Many non-stellar objects such as AGNs, including quasars and blazars, radiate in UV. Under special conditions, UV afterglows of γ–ray bursts can also be observed in UV (Roming et al. 2009). The importance of UV science means that several UV satellite projects are currently being implemented and a few others are in the conceptual phase. There are several UV missions currently in orbit. However, virtually none of the current or planned projects will provide the possibility of long-term observation of several dozen or even several hundred objects simultaneously for a period of a few months. The UVSat project proposed by us **fills in a specific niche in the research of hot objects**, which currently has no competition. It is also complementary to planned and existing space missions. Especially noteworthy is that UVSat observations will come after the delivery of the final results of the Gaia astrometric mission. Knowing distances to most of the objects that we plan to study will move many of these studies to a much higher level.

The possibility of two-colour observations, in UV and in the visual is also extremely important. A similar possibility is currently present in the BRITE-Constellation, in which out of five working telescopes two are equipped with blue filters, the other three – with red filters (Weiss et al., 2014). With the possibility of two-colour observations, however, UVSat would be – in contrast to BRITEs – an autonomous observatory. The advantage of two-colour observations with one UV band is that many phenomena that are the sources of variability have a completely different behaviour in UV and in the visual. For pulsating stars, the ratio of amplitudes in UV and visual domain is key to mode identification and, hence, successful asteroseismology. The ability to perform simultaneous observations with the second telescope is also of great importance for two other reasons: (i) the visual telescope can observe objects that are out of the range of the UV telescope, (ii) it can be used as a backup device for tracking the satellite, which in the case of failure of tracker will ensure the safety of the mission.

# 3. Photometric UVSat – science case

In this chapter we discuss objects and phenomena for which observations conducted with UVSat can produce results that are significant from the point of view of science. We also present the most favourable parameters in order to achieve the assumed scientific goals. The observational constraints for a given class of objects/phenomena have been highlighted in blue.

## 3.1. Pulsating hot main sequence stars

The most important processes associated with the chemical evolution of matter in galaxies occur in massive stars. Their internal structure and evolution, even in the longest phase of evolution, i.e. the main sequence, are still not sufficiently well understood. One of the promising techniques that can help in the study of stellar interiors, and thus in understanding the evolution of massive stars, is asteroseismology. In the recent years, this technique has gained enormous observational support in the form of precise photometric data from space missions. In general, asteroseismology is based on matching the frequencies of the observed pulsation modes with theoretically determined frequencies from the model. This allows one to find the best parameters of the model (and thus the star). At the same time, the technique can be used for testing the input physics mainly by satisfying the requirement that observed modes must be excited in the models.

Fortunately, pulsations are quite common among massive stars in the upper main sequence. We find there four main types of pulsating stars: in the upper part, the β Cephei and slowly pulsating B-type (SPB) stars, at the intersection of the main instability strip with the main sequence – δ Scuti and γ Doradus stars. In these four types of pulsating stars two types of pulsation modes are observed: pressure (p) modes (excited in β Cep and δ Sct-type stars) and gravity (g) modes (SPB and γ Dor-type stars). The mechanism of pulsation of β Cep and SPB stars was explained more than two decades ago, after the revision of stellar opacities (Moskalik & Dziembowski 1992, Kiriakidis et al. 1992, Cox et al. 1992, Dziembowski & Pamyatnykh 1993, Dziembowski et al. 1993). The pulsations in these stars are excited by the κ mechanism, effective due to the maximum opacity for the temperature of about $2 \times 10^5$ K, which occurs due to the large number of bound-bound transitions in the ions of iron-group elements. This is the cause of the high sensitivity of pulsations in these stars to metallicity (e.g. Pamyatnykh 1999). Pulsations in δ Sct stars are driven by the same κ mechanism, but working – similarly to other stars of the main instability strip – in the second helium ionization zone (e.g. Chevalier 1971).

Finally, pulsations in γ Dor stars are explained by the convective blocking mechanism (Guzik et al. 2000, Dupret et al. 2005).

Pulsations in the upper part of the main sequence allow understanding thoroughly the internal structure of massive stars during their evolution on the main sequence. This is of great importance not only to the theory of pulsation and evolution, but because of the role of massive stars in the evolution of matter (through supernova explosions) for many other branches of astrophysics. The evolutionary models of massive stars require assumptions that can be tested using asteroseismology, in particular the asteroseismology of massive pulsating stars: β Cep and SPB stars. The most important problems that can be solved with the help of asteroseismology in these stars are the following:

- The main-sequence lifetime depends very much on the range of convective overshooting, parameterized with the $\alpha_{ov}$ parameter. Consequently, the age at which the star collapses preceding the supernova explosion (Smartt 2009) depends on this parameter. At present, the determined values of $a_{ov}$ range between 0 and 0.6 (Aerts 2015) but it is not known how much of this scatter is intrinsic.
- Frequency spectra for many massive pulsating stars cannot be explained by currently available opacities. Therefore, another revision of opacities is postulated (Zdravkov & Pamyatnykh 2008, Daszyńska-Daszkiewicz & Walczak 2009, Moravveji 2016). A new maximum opacity has also been found (Cugier 2014a,b). The situation is far from satisfactory.
- What is the extent of instability strips for p and g modes and how does it depend on metallicity? Observations indicate the lack of pulsations in p-modes for early and intermediate O-type stars. From theory, in turn, it follows that these modes are unstable in such stars. This may be another hint to the revision of stellar opacities, but requires a statistically large sample of O-type stars with well-known variability.
- Are the cores of all massive stars rotating faster than the envelopes, as some seismic models suggest (Dupret et al. 2004, Pamyatnykh et al. 2004)? How much faster and what does this depend on?
- What is the role of rotation (especially fast rotation) in the excitation/damping and visibility of pulsating modes? A summary of the current situation in modelling fast-rotating stars can be found, for example, in Reese's (2015) work. The problem is difficult from a theoretical point of view, but examining the pulsating spectra of a large sample of stars with very different rotational velocities can help to explain how these stars pulsate.

To be able to talk about successful asteroseismology, one has to meet several requirements, of which the most important are three. First of all, the number of observed modes should be as large as possible: the more modes we observe, the more constraints on the model can be imposed, and thus more information about the structure of the interior of the star can be gained. Secondly, the observed modes should be identified, i.e. three quantum numbers $l$, $m$ and $n$, i.e. the degree, the azimuthal order and the radial order of the spherical harmonics (if the pulsations can still be described by the formalism of spherical harmonics) should be assigned. The identification of modes is a necessary condition for asteroseismology, because without it we cannot compare the observed frequencies with theoretical ones calculated for specific modes. Thirdly, the seismic models should be as good as possible, that is, take into account all the significant physical effects affecting the internal structure of the star and the effects associated with pulsations such as rotational coupling of modes. For asteroseismology to produce scientifically valuable results, the three above conditions should be simultaneously fulfilled. Due to much larger amplitudes in UV, UV observations would be extremely useful in mode identification for the pulsating stars discussed here.

In the context of hot main-sequence pulsating stars, it is worth mentioning the increasing number of discoveries of magnetic fields in massive stars. The discovery of magnetic fields in massive stars was a surprise due to the lack of a surface convective layer that could generate such fields in the dynamo process. Currently, it seems that these are debris fields, that is, the fields collected and reinforced during the earlier stages of the evolution of massive stars. This creates a good opportunity to study dissipation mechanisms of such fields and opens up a brand new field for studying the early stages of star evolution. Magnetic fields are also found in the β Cep stars (e.g. Silvester et al. 2009), which can affect their pulsation spectrum, as is the case of β Cephei itself (Shibahashi & Aerts 2000).

Summarizing this part, it should be noted that the observation of variability in UV (and simultaneously in the visual band) for main-sequence pulsating stars should give an unprecedented set of photometric data for at least several hundred objects, allowing for the identification of modes using amplitude ratios. At the same time, thanks to the planned precision of measurements, the examined stars should exhibit very rich frequency spectra (about 10 or more modes), which will enable effective asteroseismology for all four types of variable stars discussed in this chapter. It is also possible to achieve a breakthrough results in the interpretation of the presence of magnetic fields in massive stars and their effect on pulsations.

**Observational constraints:** Pulsating stars discussed here are the stars of spectral types B (β Cep and SPB) and A/F (δ Sct and γ Dor). The former concentrate very strongly towards the Galactic plane, so their density will be the highest for $|b| < 20°$. The latter will exhibit similar concentration, but to a lesser extent. Optimal from the point of view of these stars are two-colour observations near the Galactic plane and along the Gould Belt, with a time resolution of less than 5 minutes, aimed at obtaining the most precise photometry. It may be optimal for them to stack the images.

### 3.2. Be stars

Be stars are stars of spectral types B, whose characteristic feature is (usually variable in time) emission in the Balmer lines of hydrogen. The appearance of emission lines results from the presence of circumstellar discs in these stars, which in turn are the result of a very fast rotation. The last, very comprehensive summary of the properties of Be stars can be found in Rivinius et al. (2013). Variability in Be stars is observed in a very wide range of time scales, from hours to decades. They result from the variability of the star itself, e.g. pulsations, as well as the processes taking place in the circumstellar disk. The disk can be subject to rapid changes related to its feeding into matter by the star, as well as the distribution of matter in it, or even the dissipation of the entire disk. One of the most interesting problems, not fully resolved to this day, is the mechanism responsible for feeding disk with the matter. First, it must explain how the matter is delivered to the disk in a situation where rotation of the star, although very fast, is clearly subcritical (see, e.g., Fig. 9 in the paper by Rivinius et al. 2013). Secondly, it is also necessary to explain how to increase the angular momentum per unit mass so that at least part of the supplied matter reaches Keplerian orbits with a larger radius, thus creating a fully developed, slowly expanding Keplerian disk.

Since the discovery of pulsations in Be stars (Baade 1982, Bolton 1982), it has been argued that pulsations can be the factor that supplies matter with the missing energy and momentum, making it transported from the star to the disk. Observations of emission variability and changes in luminosity characterized by `outbursts' suggest that the process of mass transfer from star to disk is rather episodic. Evidence has also been found that outbursts and changes in the nature of pulsations are correlated (Penrod 1986, Balona & Rozowsky 1991, Huat et al. 2009). Until recently, however, only one star was known, μ Cen, for which it was convincingly shown that non-radial pulsations are responsible for mass loss episodes (Rivinius et al. 1998). This hypothesis has recently been confirmed by observations of this star and η Cen by the BRITE Constellation. As shown by Baade et al. (2016), episodes of mass transfer to disk in η Cen are related to the superposition of close in frequency g modes. Probably, this mechanism also works in the other Be stars (Baade et al. 2018). As for the transfer of momentum in the disk, this phenomenon is now described reasonably well within the framework of the so-called viscous decretion disk (Lee et al. 1991, Carciofi et al. 2012, Haubois et al. 2012, 2014).

Previous studies on the variability of Be stars in UV are very fragmentary (e.g. Doazan et al. 1993, Sharov & Lyutyi 1997) and they do not match the accuracy and coverage comparable with the observations in the visual domain. Observations with UVSat would therefore be the first long-term observation of the variability of Be stars in UV. They would allow to better characterize the origin of the variability observed in Be stars (star or disk), and – similarly to ordinary B type stars – help to identify pulsation modes. In the context of the proposed mechanism of powering the disk in matter, the identification of modes can shed light on which cases (i.e. for which modes) such an explanation is correct and whether it is only one of several equivalent or dominant mechanisms. In this sense, such observations can be crucial for understanding the physical processes in this entire class of variable stars. Observations of variability in UV should also better show the differences in the behaviour of Be stars depending on the inclination of the rotation axis.

**Observational constraints:** Be stars are distributed in the sky practically in the same way as the other spectral type B stars constituting in the Galaxy 15-20% of their population (Zorec & Briot 1997). Observational constraints are virtually the same for these stars as for the B type stars on the main sequence (Chapter 3.1).

## 3.3. The most massive hot stars

Among the most massive hot stars, we distinguish O-type stars, bright blue variables, Wolf-Rayet stars and supergiants of early spectral types. All these stars are precursors of **core collapse supernovae** (CCSNe).

### 3.3.1. O-type stars

O-type stars are the hottest main-sequence stars. These are very young (typical age of several million years) and massive ($M > 20\ M_{\odot}$) stars. The pulsation theory (Dziembowski & Pamyatnykh 1993, Pamyatnykh 1999, Deng & Xiong 2001, Miglio et al. 2007, Walczak et al. 2015) predicts pulsations in p and g modes for these stars as an extension towards the massive stars of the β Cephei and SPB pulsations. However, the observations show that while the pulsations in the p-modes are excited in the late O-type stars (Kambe et al. 1997, Pigulski & Pojmański 2008, Degroote et al. 2010, Briquet et al. 2011, Buysschaert et al. 2015), they are not seen in intermediate and early O-type stars (Blomme et al. 2011, Ramiaramanantsoa et al. 2014, Howarth & Stevens 2014). It is possible that only the high-degree modes are excited in these stars, because in the line profiles of these stars very often variability, which can be attributed to pulsations, is observed (Fullerton et al. 1996). Such modes (with a high *l*) are, however, averaged over the disk and have very small photometric amplitudes. In order to obtain a full picture of photometric variability in O-type stars, a large increase of the sample of observed stars of this type is needed. Due to the fact that they are the hottest stars at the main sequence, observations of variability in UV appear to be the optimal choice for such studies. As mentioned in Chapter 3.1, obtaining a full picture of variability due to pulsations among O-type stars can be also an important contribution to the revision of opacity.

O-type stars show also other variations associated with very large mass loss and strong stellar winds. In the changes of the spectral lines one can see the so-called discrete absorption components (DACs, Howarth et al. 1995, Lobel & Blomme 2008). Typically, two DACs per rotation period are observed (Kaper et al. 1999, Ramiaramanantsoa et al. 2018). DACs usually change with a rotation period, but do not maintain close coherence for more than a few rotational periods. UV light curves of O-type stars, covering at least several periods of star rotation (i.e. several days), should allow for an explanation of where the DACs originate from and whether they are associated with pulsations, structures in the stellar wind or a magnetic field. Many O-type stars reside in binaries. The importance of UV observations for the study of massive binaries is presented in Chapter 3.4.

### 3.3.2. Luminous Blue Variables

Luminous Blue Variables (LBV), also called S Dor-type variables, form a small and quite heterogeneous group of massive stars with the highest luminosities exhibiting significant changes in brightness on a time scales from days to decades (Humphreys & Davidson 1994; Nota & Lamers 1997, van Genderen 2001, Martayan et al. 2016). Massive envelopes created during episodic explosions surround them. The rate of mass loss in LBVs reaches $10^{-4}\ M_{\odot}$/yr (Humphreys & Davidson 1994). Even in the quiet phase, the rate of mass loss in these stars is of the order of $10^{-7} – 10^{-6}\ M_{\odot}$/yr. The cause of the violent eruptions in these stars has not yet been explained. Usually, some kind of instability is proposed, including dynamic instabilities, and binarity. Extragalactic LBVs during their violent outbursts may be mistaken for supernovae; such explosions are called supernova impostors (Van Dyk & Matheson 2012). The LBV phase is generally a phase of a very significant mass loss in the evolution of a massive star; in the course of the further evolution, these stars become mostly Wolf-Rayet stars (Maeder & Meynet 1987, Lamers & Nugis 2002). One of the most important unresolved problems related to LBV stars is the mechanism leading to violent eruptions, but changes on a shorter time scales (Lamers et al. 1998, Richardson et al. 2018) do not have a good explanation either. They could be related to the excitation of the so-called strange modes (Chapter 3.3.5).

Previous studies of photometric variability in UV for LBV stars are very sporadic (e.g. Shore 1992, Pasquali & Nota 1999) and are often limited to spectrophotometry. Long-term observations in UV, even for individual LBV stars, would be an excellent material for studying energy redistribution during different phases of variation of these stars and for explaining the sources of their variability.

### 3.3.3. Wolf-Rayet stars

Wolf-Rayet stars (hereinafter WR stars, Underhill 1968, Abbott and Conti 1987, Maeder & Conti 1994) are massive ($10 – 80\ M_{\odot}$) stars exhibiting very strong and broad emission lines in their spectra. Due to the presence of these lines, the W-R stars are divided into three sub-classes: with dominating nitrogen (WN), carbon (WC), and oxygen (WO) lines. The classic WR stars are deprived of hydrogen envelopes that were lost at earlier stages of evolution, resulting in a lack or very weak hydrogen lines in their spectra. In general, however, one can speak not about WR stars, but rather about the `WR phenomenon' if one deals with broad emission lines from hot, ionized plasma (Moffat 2015). In this situation, we also talk about the WR phenomenon in the context of much less massive planetary nebula nuclei ([WR], Tylenda et al. 1993, DePew et al. 2011, Todt & Hamann 2015) and very massive WNh (Smith & Conti 2008) and WO stars (Barlow & Hummer 1982, Crowther et al. 1998), which have hydrogen in their envelopes and undergo supernova outbursts in the course of further evolution as supernovae of type Ib and Ic. In the wider astrophysical context, W-R stars can be precursors to long γ-ray bursts. A typical evolution of the massive star is described by the sequence O - Of - WN - WC, with the density of the stellar wind increasing along this sequence. In WR stars, variability is dominated by inhomogeneity of the stellar wind.

One of the most interesting problems related to W-R stars is whether the variability of the photosphere and wind are correlated. It seems quite obvious that the variability of the photosphere should cause variation in the star wind, but the question arises whether any wind variability has its cause in the photosphere? As far as the variability of the photosphere is concerned, the magnetic field and pulsations are most often mentioned. The periodic variability of the W-R stars has been known for a long time, but due to the time scales of days and hours, and typically small amplitudes, the breakthrough was only brought with the satellite observations. The first observations of WR stars from orbit were made by MOST for stars: WR123 (WN8; Lefèvre et al. 2005), WR111 (WC5; Moffat et al. 2008) and double system with a WR star CV Ser = WR113 (WC8d + O8-9 IV; David-Uraz et al. 2012). These studies showed a lack of coherent oscillations, although all three show quasi-periodic changes, which are explained as stochastic variability. A similar picture is also shown by ground-based observations (e.g. van Genderen et al. 2013). In the periodograms of photometry of WR stars, the power usually increases towards low frequencies (red noise).

A full picture of the photometric variability of the WR stars is still unclear, due to the fact that only a few stars of this type have good observations. UVSat observations can change this situation very much. In particular, UV observations should deliver a unique collection of data that will help to understand the nature of the variability of these stars, including the role of pulsations.

### 3.3.4. Early-type supergiants, α Cygni-type variables

The variability of the α Cygni-type is observed in supergiants of spectral types O, B and A[1], which are the largest subgroup, in which this type of variability is observed (e.g. Van Leeuwen et al. 1998; van Genderen 1985,1989; van Genderen et al. 1985,1989, and other works from this series). As the most probable source of variability in these stars pulsations and inhomogeneities in the stellar wind are mentioned (Kaufer 1998; Lefever et al. 2007; Saio et al. 2013a). Analysis of pulsation in supergiants gives hope that they can be used to study the internal structure of stars through asteroseismology. This is extremely important in view of the very difficult modelling of stellar evolution in this region of the H-R diagram. A revision of opacities two decades ago brought a series of theoretical works (Glatzel et al. 1993; Glatzel & Kiriakidis 1993a,b; Kiriakidis et al. 1993,1996; Glatzel & Mehren 1996) showing that pulsations should be excited in massive bright stars, not only supergiants, but in virtually all stars discussed in Chapter 3.3. This is also confirmed by calculations, which use newer versions of opacity tables (Daszyńska-Daszkiewicz et al. 2013). It turns out that even models in the phase of core helium burning, on the so-called blue loop (Ostrowski & Daszyńska-Daszkiewicz 2015), can be unstable.

Due to the relatively long time scale of variations in supergiants, ground-based observations do not give a full picture of variability in these stars. There are relatively few satellite observations, with MOST for HD 163899 (B2 Ib II, Saio et al. 2006) and Rigel (B8 Ia, Moravveji et al. 2012) and CoRoT for HD 50064 (B6 Ia, Aerts et al. 2010) and HD 46769 (B7 Ib/II, Aerts et al. 2013). They are basically uninterrupted, but the total span of observations is about one month, so it is not much longer than the time scale of the variability. Therefore, we need not only accurate and uninterrupted data, but also long observational runs. Such runs (in two bands) can be provided with UVSat.

The study of pulsations in hot supergiants can give an estimation of the rate of mass loss and determine the evolutionary stage of these stars. Observations in UV will be important – the same reasons as for the stars presented in Chapter. 3.1 can be given here.

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[1] Sometimes also the later types, F and G, see e.g. van Genderen et al. (2004).

### 3.3.5. Strange modes

As presented above, in all types of stars discussed in this chapter, one can expect pulsations in the p and/or g modes. Besides, practically in the entire area of the H-R diagram, where the stars discussed here are expected, another kind of mods is expected – strange modes. The instability associated with these modes appears under very strong non-adiabatic conditions. A characteristic feature is the very large phase difference between pressure and density changes and – unlike for the `normal' modes – a very strong dependence of the normalized pulsation frequency on the effective temperature and mass (Gautschy & Glatzel 1990; Glatzel 1994; Saio et al. 1998, Saio 2009, Saio et al. 2013b, Sonoi & Shibahashi 2014). Although the physical origin of these modes remains a mystery, they are found in the models of virtually all stars with a high luminosity discussed in this chapter.

**Observational constraints:** All stars mentioned in this chapter are relatively rare and locate close to the Galactic plane. Nonetheless, several hundred O-type stars should be available for observations using this satellite. LBV stars are very rare objects; only some Galactic LBVs will be within the reach of UVSat. The catalogue of Galactic W-R stars currently contains 634 objects, which should mostly be within UVSat reach. Finally, the supergiants of the early spectral types are relatively numerous in comparison with the other groups of stars we discussed in this chapter and they are located close to the Galactic plane. The variability observed in stars discussed in this chapter has the shortest time scales of the order of hours or at most a dozen or so minutes. For this reason, it may be optimal to perform image stacking in order to increase the precision of the photometry, at the expense of time resolution.

## 3.4. Massive binaries

Despite the increasing complexity of evolutionary models of massive stars, the details of their evolution are not yet well understood. Its correct description is of great importance for astrophysics, because massive stars have the greatest influence on the evolution of the composition of the interstellar matter in galaxies and are precursors of the core collapse supernovae. However, even at the main sequence their evolution is not properly described. On the one hand, knowledge of masses and radii supplemented by a precise determination of chemical composition and age can be used to test models of stellar evolution. On the other hand, binary systems offer a wide range of astrophysical phenomena that cannot be studied in single stars, such as mass transfer, accretion, stellar mergers and others. Massive stars are more likely to occur in binary systems than the stars with smaller masses (Duchêne & Kraus 2013).

Stellar astrophysics is based on precisely determined fundamental parameters of stars, including their masses and radii. They can be derived for systems, which are eclipsing binaries and simultaneously double-lined spectroscopic binaries (SB2). Such systems offer the possibility of direct determination of masses and radii with a precision of 1 - 3% or better, required for testing theoretical models of the internal constitution and evolution of stars (e.g., Clausen et al. 2008). Unfortunately, the number of systems with massive components and precisely determined masses is still small (Torres et al. 2010). The catalogue of physical parameters of eclipsing binary stars, DEBCat (Southworth 2015) currently contains 374 components of double systems, for which masses and radii were determined with the precision better than 2%. Only slightly over 60 of them are more massive than 3 $M_{\odot}$, corresponding to the spectral types O and B.

Due to the more than twofold increase of the radius during the main sequence evolution, the most massive components of double systems can be used to determine the age of such systems, and indirectly – the age of stellar systems (young open clusters or OB associations) they belong to (e.g. Michalska et al. 2013). Observations in UV, in which hot stars (O and B) radiate strongly, will contribute to getting light curves of eclipsing systems with massive components, which will help in the determination of their radii. Observations in various wavelength ranges (e.g. UV and visible domains) are particularly useful for those systems where a large difference in effective temperatures is observed. Two-band observations (in particular in UV) allow in such cases to accurately determine the ratio of effective temperatures, and to model the reflection effect.

Due to their uniqueness in the context of UV observation, we discuss two specific types of massive double stars, i.e. DPV stars and massive X-ray binaries.

### 3.4.1. Double Periodic Variables

Among the double systems, Double Periodic Variables (DPVs) deserve a special attention. DPV systems were discovered thanks to many years of observations of the Magellanic Clouds as a part of the OGLE project (Mennickent et al. 2003, Poleski et al. 2010). They are characterized by the variability with two periods, in which the shorter one is the orbital period of the system related to the proximity effects and eclipses, and the other is about 35 times longer and its nature is still unexplained (Mennickent & Kołaczkowski 2010). Thanks to projects monitoring the entire sky, e.g. ASAS (Pojmański 1997) or NSVS (Woźniak et al. 2004), it was possible to discover objects of this type in the Galaxy (Mennickent & Kołaczkowski 2009). Detailed photometric and spectroscopic studies of selected systems, e.g. OGLE05155332-6925581 (Garrido et al. 2013), AU Mon (Desmet et al. 2010, Mimica & Pavlovski 2012), or V393 Sco (Mennickent et al. 2012) indicate some common features that can be generalized to describe all DPV systems. They belong to a larger group of interacting binary stars in a semi-detached configuration in which mass transfer occurs (case B of binary system evolution).

Further studies of DPV systems are important for several reasons. First of all, the mechanism causing long-term variability and, what's even more intriguing, its linear relationship with the orbital period, needs to be clarified. Another problem is the location of such systems in the more general evolutionary scenario of massive binaries. They seem to be a perfect example of evolution within non-conservation models, so that they can provide data verifying detailed theoretical predictions. In the longer perspective, the explanation and construction of a physical model of the long-term variability can provide a valuable diagnostic tool, as it has often happened before in the case of the studies of periodic phenomena.

Continuous, lasting several months observations in the UV band of selected relatively bright DPV systems can provide a unique research material to characterize more accurately the rate of accretion and the structure of the accretion disk. In this wavelength range, three components should dominate the variability: the photosphere of the primary, the inner part of the disk and the hot spot. This will allow to observe regions important from the point of view of the accretion process and to characterize them better. Another problem concerns the variability of the main component. Based on data collected in the visual domain by the CoRoT satellite for AU Mon, one of the brightest DPV systems, we managed to detect many additional signs of variation in the accretion disk and short-term variation attributed to the pulsations of the primary component (Desmet et al. 2010). Data in the UV band will be crucial in this case, because they allow distinguishing the variability due to pulsations from other phenomena.

### 3.4.2. High-mass X-ray binaries

High-mass X-ray binaries (HMXB) are young binary systems composed of a hot massive ($M > 10\ M_{\odot}$) star and a compact secondary component (Kaper 1995; Liu et al. 2000; White 2002; Walter et al. 2015), most often a neutron star, a black hole or a white dwarf. In most HMXB stars, a compact object accretes only a small portion of the stellar wind from the hot companion, and therefore the rate of accretion is very small. Strong X-rays appear in two situations: when a compact component passes through a dense part of the stellar wind or when the hot component is close to filling the Roche lobe and the mass flow through the inner Lagrange point begins to dominate the accretion. This former case occurs in those HMXBs in which the fast wind comes from a very fast rotating component that has a circumstellar disk (Be star). Such stars are called Be/X-ray stars. The Be/X-ray systems constitute 2/3 of the HMXB stars. The other cases are stars in which the main component is most often a supergiant; in such stars, part of the mass may flow to the compact component by the inner Lagrange point.

Observations of HMXB systems in the optical and UV range would allow to determine some parameters of the system, such as, for example, the orbital period. In turn, this would allow checking the relationship between the neutron star's rotation period and the orbital period (Corbet's graph, Corbet 1986). Observations of Be/X-ray systems in several bands (optical, UV and infrared) will contribute to a better understanding of the accretion of the matter onto a compact object. In particular, observations of these stars during outbursts can shed light on the redistribution of X-rays. Long-term observations would allow finding the rate of accretion of matter and its impact on the orbital period of the system (Alcock et al. 2001, Coe et al. 2002). They would also enable finding and analysing pulsations and comparing them with pulsations in single Be stars (Gutiérrez-Soto et al. 2011).

Observational constraints: Massive binaries are relatively rare systems; therefore, observations will be possible only for some selected systems (especially for DPV and HXMB stars). Since the primary components in these systems are O and B-type stars, their distribution in the sky is similar to single O and B-type stars. The time scales of variation are also similar. Therefore, the observational requirements will be very similar to those presented in Chapter 3.1.

## 3.5. Binary stars with small and intermediate masses

For systems with small and intermediate masses, despite the fact that many more such systems have precisely determined masses, the possibilities that can be provided in this respect by UVSat should bring significant discoveries. In this context, the most important observations in UV will be for systems with a large difference in effective temperatures, in which one of the components is a hot (not necessarily massive) star. Here we discuss algols and low-mass X-ray binaries a little bit more widely, but this conclusion holds also for symbiotic and cataclysmic stars, which are discussed in Chapters 3.7 and 3.8, respectively.

### 3.5.1. Algols

Algols (Budding et al. 2004) are detached or semi-detached systems after or at the final stage of mass transfer between components that resulted in the reversal of the mass ratio of the components (e.g. van Rensbergen et al. 2010). Like other binary systems with (semi)detached components, these objects are suitable for determining basic stellar parameters. The most important aspect of their research is that these close binary systems are in the final stage of large-scale mass exchange between components. In the classical algols, a donor is already an evolved (subgiant or giant) cold and low-mass star with a convective envelope. These systems are therefore suitable for studying the magnetic activity of stars. Magnetic spots can be seen in the light curves. On the other hand, they are suitable for testing more complex evolutionary scenarios than is the case of a single star. The loss of mass and angular momentum from the system is still a poorly recognized aspect (e.g. Deschamps et al. 2015). The high magnetic activity of algols is probably crucial to the loss of angular momentum.

The theory of the evolution of binary systems suggests a series of characteristics that algols may have. The lack of such stars with a total mass of less than about 1.6 $M_\odot$ could indicate that there is no significant mass loss from the system. The lack of algols with a total mass greater than about 7 $M_\odot$ may indicate that the donor has a degenerate helium nucleus, which prevents it from evolving into the supergiant phase. The lack of systems with a mass ratio greater than about $q = 0.6$ may indicate that up to this point (along with the mass exchange $q$ decreases from values greater than 1) the mass exchange is violent/unstable. These and other aspects can be monitored observationally as long as the parameters of many algols with at least moderate accuracy are known.

### 3.5.2. Low-mass X-ray binaries

In contrast to the HMXB stars discussed above (Section 3.4.2), low-mass X-ray binaries (LMXB) are old, evolutionary advanced systems. Unlike their massive counterparts, accretion occurs only through the inner Lagrange point (e.g. Frank et al. 1992). In these systems, the mass of the donor is smaller than 1 $M_\odot$. Due to the high angular momentum of the flowing matter, an accretion disk is formed around a compact secondary component (Pringle & Rees 1972). The processes of viscosity and internal friction lead to the conversion of potential energy of the disk matter into thermal energy, which warms its inner regions to temperatures of several million K, causing it to become a source of X-ray radiation. The cooler disk regions radiate in UV and visible domains. LMXB systems are investigated due to the details of accretion processes, but also to the nature of the compact component, which is most often a neutron star. Also known are about 20 LMXB systems whose compact components are black holes (Remillard & McClintock 2006).

**Observational constraints:** Binary systems with less massive components, in particular algols, are quite common. They concentrate mainly towards the Galactic plane, because there are more stars there, but one can also find them far from it. LMXB systems are rare and usually also much fainter than algols, so that only selected brightest objects will be within the reach of UVSat. Time scales of variation can be relatively short, so observations with time resolution of 1 minute would be optimal for them.

## 3.6. Chemically peculiar stars, rapidly oscillating Ap (roAp) stars

The atmospheres of the stars in the upper part of the main sequence are great laboratories enabling the study of processes related to the transfer of radiation. In the case of luminous stars, the luminosity is large enough to cause a stellar wind. The atmosphere of the fainter, colder stars is relatively calm, which allows the onset of diffusion. Diffusion, under the influence of radiation and gravity, significantly changes the chemical composition of the star's atmosphere, which becomes chemically peculiar (CP).

CP stars form a very diverse group. Their common features are significant differences in chemical composition compared to the composition of the atmosphere of a similar star with no peculiarities. These stars differ, among others, in the degree of peculiarities of the chemical composition, the type of elements whose abundances are unusual, the vertical and horizontal structure of the atmosphere, the variability, stability of the rotation period and the presence and intensity of the magnetic field.

In general, the CP stars form sequences of magnetic and non-magnetic stars in the H-R diagram. The magnetic sequence contains mainly Ap/Bp stars. The cooler Ap stars exhibit mostly peculiar abundances of Cr, Sr and Eu, the hotter Bp stars are chemically peculiar mainly due to the overabundance of Si. The non-magnetic sequence contains the Am/Fm stars and λ Boo stars (effective temperatures below 10,000 K) and the HgMn stars (effective temperatures above 10,500 K). Above about 16,000 K, the magnetic and non-magnetic sequences become less pronounced. HgMn stars combine with a fairly inhomogeneous group of stars with a reduced value of He (He-weak, He-w). Some of these stars do not exhibit a strong magnetic field (P, Xe and Ga peculiarities appear, however), others are clearly magnetic and display peculiar lines of Sr, Ti and Si, similarly to Bp/Ap stars. At even higher effective temperatures, we have stars with high He content in atmospheres (He-strong, He-s), which have strong magnetic fields.

Variability of brightness and spectrum is a typical feature of many CP stars. There are many reasons for observed variations, including pulsations. The most common type of variability in these stars is the rotational variability resulting from the presence of spots on the surface of the CP stars ($\alpha^2$ CVn-type variability). Typical amplitudes are of the order of tens of mmag. Detailed maps of the distribution of elements on the surface can be reproduced, for example, by means of the Doppler imaging (e.g. Kuschnig et al. 1999, Lüftinger et al. 2003).. The reason for the observed rotational variability is mainly the uneven distribution of chemical elements on the surface of the stars, combined with redistribution of the flux and rotation of the stars. The blocked far-UV flux is redistributed in near-UV and visual domains (therefore the variation in UV is in anti-phase with variability in the visible domain). The redistribution of the flux occurs via bound-free (e.g., Si) and bound-bound (e.g., Fe and Cr) transitions.

A very interesting subgroup of CP stars comprises so-called rapidly oscillating Ap (roAp) stars, lying within the δ Sct instability strip in the H-R diagram. They were discovered over thirty years ago (Kurtz 1978, 1982), currently we know about 60 members of this group. The pulsation periods of these stars range between several and dozen minutes and are explained as high radial order p modes (Kurtz 1990). A characteristic phenomenon observed for these stars are changes in pulsation amplitudes with the rotational phase, which is explained by the oblique rotator model, in which the pulsation axis coinciding with the magnetic axis is inclined to the rotation axis (Kurtz 1982; Bigot & Dziembowski 2002). The mechanism of the excitation of pulsations in these stars is not yet well understood (e.g. Cunha & Perraut 2013).

Variability of CP stars in UV was analysed on the basis of space observations from OAO-2, TD1 and IUE. The observations show that changes in brightness at shorter wavelengths may be in the antiphase to the light changes at longer wavelengths. In some wavelengths the variability may disappear or its amplitude may be very small. Amplitudes of variability in UV are higher compared to the visible part (e.g. Krtička et al. 2015). The ultraviolet part of the spectrum is crucial for understanding the properties of chemically peculiar stars. The analysis of UV data enables detailed testing of models for the distribution of chemical elements on the surface of the star and the analysis of vertical gradients of the abundances.

**Observational constraints:** The stars discussed here belong to Population I, so they are concentrated in the sky mainly in the Galactic plane, although they can also be found quite far from it. They are relatively bright, so within the reach of UVSat observations there should be a lot of such objects. Due to the lower effective temperatures, these are objects weaker in UV than most stars discussed above. Rotational variability has time scale of days, but roAp pulsations occur on a time scale of a few minutes. For the former, a time resolution of a dozen or so minutes is enough, for the latter the optimal time resolution would have to be shorter than a dozen or so seconds.

## 3.7. Bright symbiotic stars, symbiotic novae

Symbiotic stars are binary systems with orbital periods ranging from 200 days to more than 20 years, composed of a giant of the late spectral type and a compact hot star (most often a white dwarf) surrounded by the ionized nebula. The components of these systems interact with each other in such a way that the red giant loses mass in favour of its hot companion. In most symbiotic systems, the red giant does not fill its Roche lobe, and the mass transfer takes place by capturing the wind from the red giant. An accretion disk may also be created, but this is not a rule. The UV radiation from the accreting white dwarf ionizes partly the nebula formed by the stellar wind from the red giant, which produces emission lines observed in the optical and UV spectra (Kenyon 1986, Sokoloski et al. 2006).

Variability in symbiotic stars is observed on very different time scales. The longest variations (years, decades or even centuries) can be caused by eclipses, semi-regular or regular (when the cool component is Mira variable) pulsations, proximity effects (mainly the deformation of the giant, i.e. ellipsoidal effect, and reflection effect), nebula reaction to the energy radiated by the hot component or finally dust extinction. In all these cases, the variability in the visual domain is dominated by the cool component, while the UV variability is determined by the hot component and the accretion disk.

Some symbiotic systems show fast stochastic brightness changes (flickering) in the visual domain, with amplitudes ranging from several thousandths to several tenths mag (e.g. Zamanov et al. 2004). Time scales are usually of the order of minutes or hours. At present, Z And is the only symbiotic star with a well-defined flickering period of 28 minutes, attributed to the rotation period of the accreting magnetized white dwarf (Sokoloski & Bildsten 1999). Flickering amplitudes increase towards short wavelengths. It can therefore be expected that the amplitude of flickering in UV will be greater than in the optical domain (see e.g. Luna et al. 2013).

Many symbiotic stars, in particular symbiotic novae (hereinafter SyN) show violent brightenings (outbursts). They usually have amplitude of 1 to 5 mag and last from several months to several dozen years in the case of SyN. Their amplitudes, duration and shape of the curve are usually not predictable, and there may be significant differences between successive outbursts. There is a lack of systematic observations of symbiotic stars in UV, both in the quiet state and during outbursts.

The symbiotic stars are important because they exhibit activity that is not observed so easily in other binaries. They are therefore an interesting laboratory for studying such physical processes as: (i) loss of mass by red giants and formation of planetary nebulae, (ii) accretion on compact stars and the evolution of eruptions similar to those in novae, (iii) photoionization and radiative transfer in gaseous nebulae (Kenyon 1986). Symbiotic systems are useful in studying the late stages of the evolution of stars with small and intermediate masses, and give the opportunity to study many aspects of the interaction of components and the evolution of binary systems. The relationship between symbiotic systems and other types of binaries (e.g. cataclysmic systems) is key to understanding the role that these systems play in the formation of stellar jets, planetary nebulae, novae, supersoft X-ray sources (SSXS) or type Ia supernovae. Understanding mass transfer and accretion processes in these systems is important not only to understand their current state, but also to estimate the incidence of such systems or in general the systems with evolved giants (Mikołajewska 2012).

Observations of variability of the brightest symbiotic systems in UV should allow to increase the number of systems in which flickering is observed and to discover systems with a magnetic white dwarf. Since the source of flickering is the accretion disk, it will give the opportunity to study accretion in such systems. This should allow diagnosing the rate of accretion and various states of the accretion disk. Such research should, for example, help to verify the `combination nova' model proposed recently for explosions in Z And (Sokoloski et al. 2006).

**Observational constraints:** Symbiotic stars are relatively rare objects. Currently, about 200 such systems are known (Belczyński et al. 2000), although the number of candidates for such stars is much larger (e.g. Corradi et al. 2008). The time scales of variability are usually relatively long, although flickering observations should be made with a time resolution of a minute or even smaller.

## 3.8. Bright cataclysmic variables, novae

Cataclysmic variables (CVs) are close binary systems in which one of the components is a white dwarf accreting matter from a low-mass main-sequence star filling its Roche lobe (Hellier 2001; Warner 2003). Such systems are formed from wide systems that, after passing the common envelope phase (Paczyński 1976), tighten the orbit by emitting gravitational waves and/or magnetic braking. In systems in which the white dwarf has a strong magnetic field (polars or AM Her-type systems) it is not possible to directly accrete matter from the disk; in such systems, the matter is intercepted by the magnetic field of the white dwarf and flows to it near the magnetic poles. The rotation of white dwarfs in such systems is synchronous. In systems with weaker magnetic fields (intermediate polars or DQ Her stars, Patterson 1994) rotation is not synchronous, but the magnetic field is so strong that it does not allow the formation of a disk in the immediate vicinity of a white dwarf surface. Similarly as in the AM Her systems, the matter flows down to the white dwarf along the magnetic field lines near the magnetic poles. Typical orbital periods in the CVs range from 75 minutes to 6 hours with a characteristic period gap between 2 and 3 hours (e.g. Knigge 2006). Some CVs are eclipsing stars.

Variability of CVs is characterized by outbursts associated in novae with the onset of thermonuclear reactions (fusion of hydrogen into helium) at the base of the accumulated matter on the white dwarf surfaces or (in dwarf novae) with the instabilities in the accretion disk and changes of accretion rate. These outbursts reach several or even a dozen (for novae) mag in the visual domain, and can be even larger in UV. Depending on the nature of the variability, the CVs are divided into a number of types; the most numerous are the so-called dwarf novae. There are several types among them: the most common are U Gem stars showing quite regular outbursts, SU UMa stars (with so-called superoutbursts), which in turn are divided into three subtypes (ER UMa, SU UMa and WZ Sge) and stars of the Z Cam type (with longer periods without outbursts). In addition to the variability associated with outbursts, the variability related to the binarity (eclipses), proximity effects, and pulsations of white dwarf (Warner & van Zyl 1998) are observed in some CVs. These are pulsations in the g modes, of ZZ Ceti type (see Chapter 3.11). We currently know more than a dozen CVs with a pulsating white dwarf (Szkody et al. 2015).

A special group of CVs are (classic) novae, for which outbursts have the highest amplitudes. In some of them (in the Galaxy we know 10 such stars) outbursts were observed more than once. These are so-called recurrent novae (Schaefer 2010). It is suspected, however, that on a sufficiently long time scale all novae are recurrent, but the intervals between outbursts are sometimes counted in thousands of years. White dwarfs in the recurrent novae are quite massive, which leads to the conclusion that they may be precursors of type Ia supernovae (Kato & Hachisu 2012). This hypothesis, however, is criticized (Schaefer 2014) and must be verified.

Cataclysmic variables constitute the largest population of close binary systems. Due to the fact that they are relatively bright and nearby, they help to understand the complex processes of accretion and outflow in close binary systems and to supplement our knowledge about the evolution of such systems. This has important implications for understanding the processes leading to the outbursts of type Ia supernovae, the formation of LMXB stars or millisecond pulsars. For the stars themselves, the most important problems are: (i) reproducing the observed distribution of orbital periods, including the limiting values of these periods, (ii) understanding the evolution of mass of white dwarfs in view of the competing processes of accretion and outbursts, during which the white dwarf loses mass, (iii) understanding the nature and properties of white dwarfs, (iv) study the accretion processes in the context of the presence of a magnetic field of varying intensity. Due to the fact that the CVs radiate most of the energy in the ultraviolet, this is a key domain for the study of these objects. The spectroscopy in far or even extreme UV (de Martino & Gänsicke 2009) is very important for resolving many problems in CVs, but photometry in this domain, practically so far non-existent, should open up completely new possibilities of studying these stars. CVs in the quiet phase are, however, relatively faint objects. This means that these are objects that will be within the scope of UVSat observation only during outbursts. However, because the effective temperatures of white dwarfs in the CVs are quite high, approximately 18,000 K below and 26,000 K above the period gap (Urban & Sion 2006), a few systems should be visible to UVSat – also in the quiet phase.

**Observational constraints:** The latest edition of the catalogue of cataclysmic stars, LMXB and similar objects (Ritter & Kolb 2003) contains almost 1,200 CV stars. They are, therefore, very common systems, due to the advanced stage of evolution, quite old, and therefore present both close to and far from the Galactic plane. Due to the short time scales of virtually the majority of variations in these stars (especially eclipses and pulsations), observations with a time resolution equal to a maximum of a few seconds are optimal for these objects.

## 3.9. Early phases of supernova explosions

Explosions of supernovae, one of the most energetic phenomena in the universe, are still not well understood. This applies in particular to core collapse supernovae (Ib, Ic, II) ending their lives of massive stars. It is mainly these supernovae that determine the chemical evolution of cosmic matter. Observations of the early stages of the supernova explosion in UV provide an excellent opportunity to study the properties of massive exploding stars, including their radii and chemical composition (Rabinak & Waxman 2011). When a supernova shock from the nucleus reaches the outer layers of the star, a situation arises in which the optical depth becomes such that the electromagnetic radiation can eventually escape the star (e.g., Nakar & Sari 2010). This shock breakout flare (SBOF) should first be visible in X-rays (where it lasts for a short time, the order of minutes) and then in UV (where it lasts longer, for hours) and visual domain. Its duration is proportional to the pre-supernova radius (Sagiv et al. 2014), which allows its determination. Observations of this phenomenon are very scarce (e.g. Schawinski et al. 2008). IUE, HST and GALEX recorded several supernova light curves in UV. The most numerous sample of light curves of supernovae in UV (over 300) is the result of ten years of observation with the UVOT telescope on-board the Swift satellite (Brown et al. 2015).

Among the supernovae for which the appearance of SBOFs can be expected are also the superluminous/ultra-luminous supernovae (SLSNe). This is a recently discovered class of supernovae that at the maximum are at least 2 mag brighter than Type Ia supernovae (Quimby et al. 2011). The fall of their brightness after the maximum is not explained by known mechanisms that successfully model this phase for known supernova types (e.g. radioactive decay of $^{56}$Ni). A characteristic feature of these supernovae is also high brightness in UV. The mechanisms of their formation are not yet known; the proposed ones are colliding envelopes, pair-instability or magnetars (e.g. Quimby et al. 2011, Gal-Yam 2012, Sukhbold and Woosley 2016). The most luminous supernova of this type is SN 2015L = ASASSN-15lh (Nicholls et al. 2015, Dong et al. 2015, 2016). For this supernova, the observations were not made fast enough to register SBOF, but the star brightened up in UV dozens days after the maximum (Brown 2015, Godoy-Rivera et al. 2016, Brown et al. 2016).

An estimation of the number of SLSNe in a $10° \times 10°$ field made by Cosimo Inserra (Queen's University Belfast, UK, private communication), assuming the detection threshold of 19 mag in UV, two different evolutionary star-forming scenarios from the work of Cole et al. (2001) and Bouwens et al. (2011), and the ratio of SLSNe to CCSNe from McCrum et al. (2014), gives the number of $2 \pm 1$ SLSNe per year. This means that there is a chance to obtain this type of unique observation with UVSat if the observational requirements presented below are fulfilled. In this case, there is also a chance to get SBOF observations for many `normal' supernovae. For SLSNe, such observations would be of great importance, as they would allow limiting the models, both in terms of the outburst mechanism and the character of the progenitor (single or double star). In a broader context, this may be important for studying γ-ray bursts and the chemical evolution of galaxies.

**Observational constraints:** Detection of early stages of supernova explosion, including the detection of SBOF, requires monitoring of a large number of objects (galaxies) in the field of view. Due to extinction, the fields far from the Galactic plane are preferred. The next requirement is a large photometric range, which can only be possible with long exposures or image stacking. If the limitations of downloading will prevent the transmission of whole images to the ground, the situation can be solved by real-time on-board analysis of the fragments of the image around all relatively bright galaxies. This would allow both detection of SNe explosions (including SBOFs) and triggering simultaneous spectroscopic and photometric observations using ground-based instruments.

## 3.10. Luminous classic variable stars (Cepheids, RR Lyrae stars)

Classical Cepheids (hereinafter CC) are evolved population I stars. Most of them fall into the instability strip (IS) at the phase of core helium burning. About 10% of CCs cross IS during their way to the red giant branch after descent from the main sequence – this is so-called first crossing. CCs are relatively massive stars (4 – 14 $M_{\odot}$). Population II Cepheids (hereinafter PTC) and RR Lyrae-type stars (hereinafter RRL) are two types of classical pulsating stars of Population II. They are low-mass (masses in the range of 0.5 – 0.7 $M_{\odot}$) pulsating stars, burning helium in their cores, and located at the intersection of IS with the horizontal branch (RRL) or above it (PTC). Both Cepheids and RRLs are one of the most important pulsating stars in astrophysics. CCs, due to the fact that they are very bright and obey the period – luminosity (absolute magnitude) (P – L) relation, play a fundamental role in determining the distance scale in the Universe (Freedman & Madore 2010). The P – L relation also exists for PTCs, and the brightness of RRL stars (in the *V* band) are independent of period, though they depend on the metallicity. This means that both PTCs and RRLs can be used as independent distance indicators for objects in the Galaxy, Local Group galaxies, and even beyond (CCs). All three types of classical pulsating stars can be used to study the structure of the Galaxy (e.g. Pietrukowicz et al. 2015) and other stellar systems containing the old population of stars, and their chemical and kinematic evolution. A good understanding of their nature is therefore important not only from the point of view of pulsation theory, but in a much broader astrophysical context.

For many decades, CCs and RRLs were considered to be pulsating stars only in radial modes. This simple picture changed after the discovery of non-radial modes with small amplitudes in Cepheids in the Magellanic Clouds (Moskalik et al. 2004, Moskalik & Kołaczkowski 2009, Soszyński et al. 2008, 2010). Non-radial modes were also found in RRL stars pulsating mainly in the first overtone (Netzel et al. 2015, Moskalik et al. 2015). In this context, space photometry, especially that made by Kepler, very few in the case of Cepheids, much more abundant so in the case of RRL stars (Kolenberg et al. 2010, Szabó et al. 2010, Benkő et al. 2010, 2014, Moskalik et al. 2015) have proved very useful.

Classical pulsating stars are relatively cool, which means they are not very bright in UV. The most interesting problems related to the study of these stars, listed below, can thus be best explored using the observations in the optical range. Nevertheless, for the brightest of them, UV observations can provide very important information. One of them is the identification of the pulsation modes, especially non-radial modes (see below). Amplitudes of RRL stars in near UV range can reach 3 mag, and in far UV – even 6 mag (Wheatley et al. 2012, Kinman & Brown 2014, Siegel et al. 2015). The UV and visual light curves can help to estimate the effective temperature changes over the pulsation cycle. Wheatley et al. (2012) also showed that UV brightness near a minimum could be used to determine the metallicity of these stars.

The precise UV/visual space photometry can be used in particular to: (i) search for non-radial oscillations, (ii) search for high overtones of radial modes, (iii) study of the stability of light curves, including the Blazhko effect, a periodic or quasi-periodic phenomenon of modulation of amplitude and phase, (iv) study of the stability of the pulsation phase, (v) search for bimodal radial oscillations, (vi) search for bimodal resonant oscillations in Cepheids, (vii) search and analysis of the doubling effect for CCs, which may allow to determine the exact mass – luminosity relation for these stars, (viii) search for chaotic phenomena in PTCs (e.g. Smolec 2016).

**Observational constraints:** Classical Cepheids are relatively young stars, thus concentrated towards the Galactic plane, while RR Lyrae stars are evolutionary advanced stars present in the Galactic halo and numerous also far from the Galactic plane. Due to the relatively long pulsation periods (from several hours to tens of days) and the small amplitudes of the searched modes, the most important for these stars are the longest coverage in time and the best accuracy of photometry.

## 3.11. Pulsating hot compact stars

Hot compact objects (white dwarfs, nuclei of planetary nebulae, hot subdwarfs) are objects attractive for UV observations due to their high effective temperatures and pulsations observed in them, which allow probing interiors of these evolutionary advanced objects. We will discuss here two groups: pulsating white dwarfs and stars preceding the phase of the white dwarf, that is, the nuclei of planetary nebulae and PG 1159-type objects (Chapter 3.11.1) and hot subdwarfs (Chapter 3.11.2).

### 3.11.1. Pulsating white dwarfs and pre-white dwarfs

White dwarfs form the largest group of compact objects that are products of the evolution of low and intermediate-mass stars. Studying their incidence and properties is one of the best ways to get to know the evolutionary channels of stars. The classification of white dwarfs related to the chemical composition of their atmospheres and the appearance of their spectra distinguishes white dwarfs with hydrogen (DA), helium (DB) and carbon-oxygen envelopes (DO, PG 1159). Among white dwarfs, pulsating stars deserve a special attention, because they open the possibility of studying their interiors by means of asteroseismology. Asteroseismology of the white dwarf precursor, PG 1159-035 (Winget et al. 1991), remains to this day one of the best examples of the application of this technique.

At present, among the white dwarfs (WDs) and stars in phases preceding the WD phase (pre-WD), we distinguish several types of pulsating stars. The pulsation period of WDs are very short, from about 100 seconds to just over an hour. Due to the lowest effective temperatures ($T_{eff}$), ZZ Ceti (DAV) stars are least attractive for UV observations. These are the most numerous pulsating WDs of DA type (with hydrogen atmospheres) with $T_{eff}$ ranging from 10.4 to 12.4 kK. They are located at the intersection of the classical instability strip with WD cooling sequence. Their periods of pulsation are in the range of 100 - 1400 s, excited low-degree g modes of low and intermediate radial orders. The pulsation mechanism of ZZ Cet stars is associated with convection and ionization of hydrogen (Brickhill 1991, Goldreich & Wu 1999). The second group of cool WDs are recently discovered white dwarfs with extremely low mass (ELM), 0.15 - 0.3 $M_{\odot}$, being products of the evolution in a double system, in which they never came for helium burning in a degenerate nucleus (Brown et al. 2010). We know several dozens of stars of this type, in some of them pulsations were discovered (e.g. Gianninas et al. 2016).

The stars located on the H-R diagram in the area of so-called `knee' of the evolutionary track leading from the asymptotic giant branch (AGB) to the WD cooling sequence have very hot atmospheres. This group includes the nuclei of planetary nebulae, PG 1159 stars (with atmospheres consisting of He, C and O), and WR stars of planetary nebula nuclei. They are direct descendants of about 20% of post-AGB stars that pass the so-called late helium flash (Iben et al. 1983). The effective temperatures of these stars reach up to 170,000 K, so they are very bright objects in UV. In this area of the H-R diagram we also find pulsating pre-WDs, i.e. stars of the GW Vir type, also called DOV stars with $T_{eff}$ in the range of 75 - 170 kK, in which pulsations are excited in the zones of partial ionization of oxygen and carbon. We know about 20 stars of this type (Quirion et al. 2007, Quirion 2009, Woudt et al. 2012), from which the planetary nuclei (PNi) are sometimes distinguished. The excited modes in these stars are also low-degree g modes with low and intermediate radial orders. Asteroseismology of these stars can be very useful for understanding the evolution of the fast pre-WD phase. As mentioned above, the asteroseismology of GW Vir itself (Winget et al. 1991) is one of the best examples of using this technique for studying stellar interiors.

In the area of intermediate (for WDs and pre-WDs) effective temperature, from 19 to 32 kK, we find three types of pulsating hot WD: V777 Her = DBV stars, pulsating DQ type white dwarfs (DQV) and a rather small group of so-called hot DA type WDs. DBV stars are WDs with helium envelopes, in which the mechanism of pulsation is similar to that in ZZ Ceti stars, only that this time the helium ionization is important. We currently know about 20 stars of this type (Østensen et al. 2011). Also pulsating are very rare DQ type white dwarfs (Dufour et al. 2007), in which spectra carbon lines are visible. Their origin is not explained. They seem to have strong magnetic fields. Finally, the hot type DA WDs (Shibahashi 2005; Kurtz et al. 2008, 2013), with effective temperatures around 30 kK appear to be WDs with very thin hydrogen envelopes. Therefore, the pulsation mechanism working below such envelope (in the He layer) is the same as in the DBV stars.

The most important problems associated with WD pulsations are related to the evolutionary scenario, diffusion in atmospheres, magnetic field and rotation. All these phenomena and problems can be tested by means of pulsations. UV observations are less important in the context of the identification of modes, which for many pulsating WDs is possible on the basis of regularity in their frequency spectra. However, it is important that the amplitudes in UV are much larger than in the visible domain, which may allow detection of a larger number of modes.

### 3.11.2. Pulsating hot subdwarfs

Hot subdwarfs were discovered in the middle of the last century (Humason & Zwicky 1947). They are low-mass (0.5 $M_{\odot}$) evolved stars burning helium in their cores (Heber 1986, Saffer et al. 1994, Heber 2016) lying in the blue part of the horizontal branch, the extended horizontal branch (EHB). They are in the course of the evolution directly to WDs. The end of the last century brought the discovery of pulsations in these stars. The pulsations have become a perfect tool to increase the knowledge on both their internal structure and evolution. Up to now, using ground-based observations, about 100 pulsating hot subdwarfs have been detected. Since 2009, pulsating hot subdwarfs has also been observed with the use of Kepler. 18 objects of this type were detected during the mission K1, a similar number in the K2 phase. Hot subdwarfs can be divided into sub-types with O-type (sdO, hotter) and B-type (sdB, cooler) spectrum. First, pulsations were found only in the sdB stars (Kilkenny et al. 1997). These stars can pulsate in both p modes (V361 Hya-type stars) and g modes (V1093 Her-type stars). Both types differ in effective temperature and gravity. The former are hotter and have higher surface gravity, the latter – cooler and have lower gravity. There are also a few known sdB stars pulsating in both p and g modes simultaneously (hybrid DW Lyn-type stars with intermediate $T_{eff}$s).

A breakthrough in the observation of pulsations, especially identification of modes in these stars, resulted in the observations of sdB stars by Kepler (e.g. Reed et al. 2010, Baran et al. 2011). In the Kepler sample, the most numerous are the V1093 Her-type stars. Observations from Kepler made it possible to identify the modes of pulsation (Reed et al. 2011). For this purpose, both the presence of multiplets, which indicate the mode degree and the azimuthal order, as well as asymptotic relations were used. These relations allow determining both the degree of the mode and its radial order. With rotational splittings, rotation periods have also been estimated for many stars. This information is necessary to build theoretical models of sdB stars. To achieve this goal, long (several months) continuous observations are needed. This ensures sufficient frequency resolution and precision in determining amplitudes. An additional tool for identifying modes in pulsating subdwarfs is observation in many filters. The identification method based on amplitude ratios in different bands (Daszyńska-Daszkiewicz et al. 2003) has been successfully used to identify modes in several sdB stars observed from the ground (e.g. Baran et al. 2008).

Pulsations in the sdO stars have been detected relatively recently. Several pulsating sdO stars with $T_{eff}$ in the range of 48 – 54 kK were found in the globular cluster ω Cen (Randall et al. 2011), but these stars are much colder than the sdO stars in the Galaxy and seem to have no counterparts among the stars of the Galactic field (Randall et al. 2014).

Many of the hot subdwarfs occur in double systems with a low-mass star of the main sequence as a secondary component, creating short-period pre-cataclysmic systems (systems following the common envelope phase). There are known orbits of about 150 such systems (Kawka et al. 2015, Kupfer et al. 2015). About 10% of them (a dozen or so) are eclipsing systems, which are referred to as HW Vir-type systems (e.g. Schaffenroth et al. 2015). One of the most interesting cases of the HW Vir system is NY Virx, in which the hot sdB subdwarf is the V73 Hya-type pulsating star (Kilkenny et al. 1998, 2003).

The problem of stellar evolution to hot subdwarfs after the red giant phase is very interesting, because the star must lose most of the hydrogen envelope at this stage. Studying the structure of pulsating subdwarfs using asteroseismology can shed light on these mechanisms. In turn, understanding the structure of sdO stars and their evolution can complement our knowledge of evolution on EHB. At present, it is not known whether the sdB stars evolve to sdO stars, or whether the sdO and sdB stars are formed in two independent evolutionary channels.

At the moment, there are no observations of time series of white dwarfs and hot subdwarfs in UV. Although the objects are relatively faint (the brightest pulsating white dwarfs have brightness in the *V* band of the order of 12 mag, the brightest hot subdwarfs, about 10 mag), their extremely high effective temperatures will help to detect the variability of the brightest objects with UVSat. A very important argument for observing these objects with UVSat is to provide long observations, which will allow separating close frequencies in their spectra. In UV, their pulsations should also have much larger amplitudes than in the visual domain. This aspect is very important especially for sdO stars.

**Observational constraints:** Both white dwarfs and subdwarfs are advanced evolutionary and relatively faint objects. For their observations, the locations far from the Galactic plane will be better. Periods of pulsation in white dwarfs and hot subdwarfs are relatively short, from just under 100 s for p modes in sdO stars to over one hour for g modes in hot subdwarfs and white dwarfs. To avoid amplitude reduction for the modes with the shortest periods, observations with relatively short exposure times (minimum of 10-20 seconds) will be necessary. For detecting g modes in hot subdwarfs, exposures can be much longer. Optimal for observing these objects would be a relatively large telescope and observations of fields located far from the plane of the Galaxy. The most difficult to observe due to low effective temperatures and faintness will be ELM white dwarfs, which may be out of reach of UVSat.

## 3.12. Stars at the pre main-sequence stage of evolution

Among stars at the pre-main sequence phase, the two dominant groups available for observations in the visual domain are the classical T Tauri-type Star, CTTS, with masses smaller than 1.5 – 2 $M_{\odot}$ and late spectral types, and Herbig AeBe type stars with masses in the range of 2 – 8 $M_{\odot}$ and early spectral types. These are young objects (1 – 5 million years old), still surrounded by protoplanetary disks. As long as the plasma from the disk is not drawn, the mass of these stars slowly increases as a result of accretion; the observed range of the accretion rate is $10^{-(8\text{-}11)}$ $M_{\odot}$/year. A small subset of CTTS stars are FU Ori type stars whose brightness in the ultraviolet and visual bands is dominated by the radiation of the accretion disk.

Below we will discuss realized and currently carried out studies of this type of stars by MOST, CoRoT and Kepler satellites, observing in the visual bands, and the targets that the proposed UVSat satellite could achieve, having a huge advantage over these satellites, due to the ability to observe in two regions of the spectrum simultaneously.

### 3.12.1. Classical T Tauri stars (CTTS)

In CTTS having magnetic fields with intensity of a few kG, the regular structure of the disk is torn apart at the distance of several stellar radii and further plasma flow from the disk to the star is controlled by the magnetosphere – it takes place in narrow streams along the magnetic field lines. Plasma, hitting the stellar surface, produces hot spots with temperatures of the order of 10,000 K. The rotation of such a spotted star is responsible for its large-scale photometric variability, reaching the highest amplitude in the ultraviolet. The mechanisms of accretion and the conditions at the interface between the disk and magnetosphere have been studied so far thanks to the broadband light curve collected continuously within a few weeks by the MOST, CoRoT and Kepler satellites. Very often the variability looks irregular, but thanks to the wavelet analysis, we know that in many cases it can be decomposed into several simultaneous `packages' of quasi-periodic oscillations (Rucinski et al. 2008, Siwak et al. 2014; Stauffer et al. 2014), which indicates unstable accretion (Kulkarni & Romanova 2008). This allows determining how the value of the internal radius of the disk changes depending on the balance between `magnetic field pressure' and `plasma disk pressure', which can be easily related to fluctuations in the instantaneous mass transfer rate.

Repeated observations of previously observed and new members of the CTTS group using UVSat will provide information on morphological changes in light curves occurring at longer time scales, e.g. due to a change in the average rate of accretion (see discussion in Siwak et al. 2016). None of the CTTS was monitored in the UV band without interruption on a time scale of even a few days. Similarly, none of them has been monitored for a long time in two bands. Simultaneous observations in the visual and UV range will allow determining accurate colour indices. The latter are needed, among others, to determine the temperatures of the spots that cause observed light changes (hot versus cold, the latter dominate in the photospheres of the so-called weak-lined T Tauri-type stars) or the separation of the observed effects of occulting the central star by the dust clumps in the disk. Although the determination of colour indices is possible from the ground, the accuracy of these observations would be 5 – 10 times worse than from the space observatory and impossible on a scale as massive as from the satellite, omitting the problem of ensuring frequent and uniformly distributed sampling in time.

The temperatures of typical hot spots on CTTS are of the order of 10,000 K, so the maximum amplitudes of light changes fall in the proposed UV band. We estimate that the amplitude of variation caused by accretion processes in this spectral range can reach 2 – 3 mag, so that observations of relatively weak stars (12 – 13 mag in this band) will be possible. Complementary observations in the visual band will enable easy reference to archival data, including the MOST, and will be used to study the evolution of the colour index as a function of star brightness.

### 3.12.2. Herbig Ae/Be stars

In contrast to CTTS, the physical interpretation of the wavelet spectra of some observed so far by the satellites Ae/Be Herbig stars, e.g. AB Aur (Cody et al. 2013) or HD 37806 (Rucinski et al. 2010) is difficult. Perhaps this is because the intensity of the magnetic fields of Herbig Ae/Be is an order of magnitude smaller than in the case of CTTS (Hubrig et al. 2015a, Fairlamb et al. 2015). According to these authors, while in stars from the Ae subgroup, accretion may still be controlled by the magnetosphere, this is not the case for the Be subgroup – the accretion in the hottest stars of this type could occur, for example through the boundary layer (Cauley & Johns-Krull 2015).

An initial list of Herbig AeBe stars available for UVSat, for which magnetic field strengths, average accretion rates and basic physical parameters were determined, includes about 100 objects. The purpose of the first photometric observations of a larger group of stars of this type with a time resolution of about 1-2 hours for several weeks or even months is to determine the relationship between the type of observed variability, determined by a specific accretion mechanism (see, e.g., Kulkarni & Romanova 2008) and known physical parameters presented in the publications cited above. In particular, we expect to determine the minimum values of magnetic field strength able to control accretion. UVSat will be able to observe a large group of stars of this type. These are bright objects and maximum emission from both their hot spots and stellar photospheres is located in UV and blue part of the visual spectrum. It can be said that the UVSat observation bands, especially UV, are ideally suited to observing these types of stars. In addition to the aforementioned scientific goals, these observations will also be used to study high-energy flares in young stars (UV observations will allow this), search for transits of thick dust clouds, and maybe even forming planets – this is also the area in which two-colour observations will help to distinguish possible transits from typical eclipses in binary stars with different photosphere temperatures.

### 3.12.3. FU Ori stars

FU Ori stars belong to the CTTS group. The most important feature that distinguishes them from typical CTTSs is the accretion rate increased by several orders of magnitude, from a typical $10^{-(8-11)}$ to $10^{-(4-6)}$ $M_{\odot}$/ year. In the light of the latest findings (Liu et al. 2016), it is most likely related to the fact that in the earliest stages of a star's life (between the so-called class I and II, or 100,000 to 300,000 years after its birth) protoplanetary disks and their surroundings are not gravitationally unstable. In this situation, most of the accreted matter falls on the protostar in violent episodes. There are other hypotheses that attempt to explain this kind of `outbursts' by the gravitational influence of the secondary component on the disk structure, or by migrating a planet with a Jupiter mass close to the inner disk radius (10 – 20 $R_{\odot}$), and then its tidal disruption and violent (on a time scale of 1 year) increase of the rate of accretion, lasting until the source of additional mass near the star is exhausted (several dozen – several hundred years).

From a practical point of view, it is important that during this outburst the temperature of the plasma in the disk grows from a typical 1 - 1.5 kK near the inner radius of the disk (for CTTS), up to 5 - 7 kK (for FU Ori stars) and remains practically constant for decades. In this situation, the radiation of the disk significantly exceeds the radiation of the protostar; it dominates over its brightness from a dozen to several hundred times, which creates excellent opportunities to study the dynamics of the most internal disk regions in the visual domain. The increase in the brightness of FU Ori itself by 6 mag in the blue band occurred in 1937 and continues to the present day. Probably the slow return of the disk to equilibrium will last for several hundred years. The first MOST satellite observations in the 2010/2011 season allowed the discovery of temporally coherent 2 - 2.5-day quasi-periodic oscillations (Siwak et al. 2013), which were explained by the inhomogeneity of the plasma in disk, spiralling towards the internal radius of the disk. The value of the internal radius of the disk was also estimated at about 5 $R_{\odot}$, which is consistent with interferometry observations (Malbet et al. 2005).

During the second MOST campaign (2013/2014) we also conducted multi-band *UBVRI* observations. Their goal was to show whether the colour indices change during the MOST run and whether the changes correlate with the total brightness of the star observed by the satellite. Although the wide-band (370 – 750 nm) MOST curve shows amplitudes of variation up to 0.07 mag, the low accuracy of ground-based observations (only 0.01 - 0.03 mag) does not allow for accurate studies of the relation between period and colour index. Such dependency should exist if the internal disk has a Keplerian rotation. Knowing the temperature distribution of the disk (Zhu et al. 2007), this may allow determining the mass of the central star. Our preliminary results suggest that the mass of FU Ori should be changed from 0.3 to 0.7 $M_{\odot}$.

High-accuracy two-band observations that UVSat could provide for FU Ori and other stars of this type would help to determine more precisely the areas of the inhomogeneity in the disk, allow to unambiguously check whether the disk rotation is Keplerian, track stability or variability during these discrepancies from homogeneity and even specify the mass of the star.

**Observational constraints:** All objects belonging to the three groups discussed above are located in several star-forming regions (SFR) a few-dozen degrees wide. Thanks to the large field of view of the satellite, it will be possible to observe all bright members belonging to a given SFR (such as Taurus-Auriga, Orion, ρ Ophiuchi, Lupus I, II, III, Corona Australis, Cynus, Cepheus) during the same run. Optimal for this project would be the largest possible telescope diameter, i.e. 10 cm or more due to the strong red colour indices of CTTS and FU Ori stars, although taking into account the sensitivity of the detectors used, this is not crucial.

## 3.13. Active galactic nuclei (AGNs)

Investigating the variability of active galactic nuclei (AGNs) in all available spectral bands is crucial for understanding the physics of their central regions, in particular the accretion on the central supermassive black hole (SMBH). In the variability studies, both changes in the lines and in the continuum are important, including correlations and delays between changes in different parts of the spectrum. The ultraviolet part of the AGN spectra (including quasars) is dominated by the thermal radiation of the internal parts of the accretion disks surrounding SMBH (e.g. Shields 1978, Sun & Malkan 1989).

Variability in AGNs (both in the continuum and in the spectral lines) is very common and observed in all spectral ranges (Ulrich et al. 1997). Relative flux changes are largest in X-ray and radio domains. In UV, they are slightly smaller, although much larger than in the optical domain (e.g. Soldi et al. 2008). As far as the sources of variability in AGNs are concerned, two mechanisms are usually considered: (i) the accretion disk response to X-ray variation in very close proximity to SMBH (e.g., Krolik et al. 1991, Breedt et al. 2010), (ii) intrinsic changes in the disk that cause changes in the rate of accretion, and consequent changes in X-ray emission. In the former case changes in X-rays should precede changes in UV and visual domain, in the latter, the relationship between changes should be reversed. This is due to the negative temperature gradient in the accretion disk. If the perturbations arising in its internal part are spreading outwards, the corresponding changes in brightness should first be observed on shorter wavelengths, and only then on longer ones. For case (ii), the sequence is reversed.

Recently, there is more and more evidence that the process (i) is the dominating one that causes the variability of AGNs. One example of the behaviour consistent with the scenario (i), and at the same time the example of using UV observations, can be a sudden brightening of the not too distant (64 Mpc) Seyfert galaxy NGC 2617. The brightening was discovered by the ground-based ASAS-SN project (Shappee et al. 2013). Observations from X-rays to infrared showed the behaviour consistent with a model of thermally radiating thin disk, in which the delay in relation to the maximum in X-rays was 2 – 3 days for UV, 3 – 6 days for the visual, and as many as 9 days for infrared (Shappee et al. 2014). Other examples of the measurement of delays in AGNs using UV observations are the papers of Cameron et al. (2012) and McHardy et al. (2014). The number of objects in which delay has been determined so far is however small and any such observation, especially UV photometry, will be very valuable. Such observations (for various types of AGNs) will allow testing accretion disk models. Depending on the object, and in particular on the mass of SMBH, the delays may be different, also very small (of the order of hours or even shorter). So in this case, a good time resolution is important.

**Observational constraints:** AGNs are distributed fairly uniformly in the sky, but their observations are possible only far from the Galactic plane, where they are obscured due to Galactic extinction. The time resolution of the order of minutes should be sufficient, therefore an observation strategy proposed for supernovae (Chapter 3.9) can be adopted for them with continuous monitoring of all known (and sufficiently bright) AGNs in the observed field.

## 3.14. Exoplanets

Transiting extrasolar planets (exoplanets) are extremely important laboratories for planetary astrophysics. Their search and investigation is one of the rapidly growing fields of modern astronomy. The first exoplanets were discovered over 20 years ago, now we know thousands of them. The Extrasolar Planet Encyclopaedia[2] lists nearly 3,800 planets discovered using various methods, including about 2,700 planets discovered by the transit method. The latter number is mainly due to the Kepler mission. The depth of a transit depends on the ratio of the radii of the planet and the star; the larger it is, the greater the decrease in the observed brightness. Photometric observations of transits along with precise measurements of relative changes in radial velocities of the central stars allow determining the full set of physical parameters of exoplanets (e.g. Winn 2010), including their masses and radii. This has a significant impact on our knowledge of their internal structure (e.g. Nettelmann et al. 2010). In order to determine the physical properties and chemical composition of planetary atmospheres, observations of occultations, i.e. the passage of the planet behind the star's disk (e.g. Deming et al. 2005) or transmission spectroscopy (e.g. Charbonneau et al. 2002) is used.

Most of the planets discovered by dedicated ground-based surveys have sizes comparable to Jupiter and orbit close to the central star (so-called hot Jupiters). Short orbital periods (several days) and large sizes make such planets relatively easy to detect by means of ground-based instruments. Meanwhile, the results obtained by Kepler indicate that the vast majority of discovered exoplanets have sizes between Mercury and Neptune, and hot Jupiters constitute a relatively small group (Marcy et al. 2014b). Particularly interesting are the planets with sizes between the Earth and Neptune, which do not have their counterparts in the Solar System. These planets have wide range of mean densities, which translates into a diversified internal structure (Marcy et al. 2014a). Among them there are rocky globes with an average density above 10 g/cm$^3$ (so-called super-Earths), as well as gaseous planets with an average density below 1 g/cm$^3$ (mini-Neptunes). Another important aspect of research in this field is the determination of whether and to what extent exoplanets are suitable for living, meaning life forms, which occur on Earth. Ground-based spectroscopic and narrow-band photometric observations made in the optical or infrared part of the spectrum (Charbonneau et al. 2002, Tinetti et al. 2007, Swain et al. 2008, Sing et al. 2011) made it possible to detect in the atmospheres of exoplanets the presence of various molecules and atoms, including sodium, potassium, water and methane, showing that the chemical composition of these planets does not differ from the one we observe in the Solar System.

Of the many studies of exoplanets, only a few were conducted in the ultraviolet domain, especially when it comes to photometric observations. Meanwhile, the observations of planetary transits in this part of the spectrum can be used to study various types of interactions between the star and the planet and to study the dispersing properties of planetary atmospheres (see, e.g., Fossati et al. 2015). The advantage of UVSat is that this instrument will enable simultaneous measurements in UV and in the visual domain. Such observations open up a number of possibilities to study the physical properties of the atmospheres of selected exoplanets. For example, observing a similar depth of transit in UV and in the visible range may indicate the presence of clouds in the upper atmosphere of the planet. These clouds outflank absorbing structures in UV (Seager & Sasselov 2000, Brown 2001, Gibson et

[2] http://exoplanet.eu/

al. 2013, Kreidberg et al. 2014, Knutson et al. 2014). On the other hand, the effect of Rayleigh scattering in the atmosphere of exoplanets will manifest itself through an increase in the depth of transit in UV (Lecavelier Des Etangs et al. 2008, Tinetti et al. 2010, de Wit & Seager 2013, Griffith 2014). In addition, it will be possible to study the planet environment and phenomena resulting from the escape of gases from the upper atmosphere, shock waves, the interaction of the planet's magnetosphere with the coronal plasma, or the presence of torus of ionized matter from the active moon (e.g. Vidotto et al. 2010; Lai et al. 2010, Ben-Jaffel & Ballester 2014, Matsakos et al. 2015). These phenomena will manifest themselves as deformations of the transit curve in UV, e.g. asymmetries.

It is predicted that within the range of UVSat there will be from several dozen to several hundred known stars with exoplanets – mainly hot Jupiters. However, it can be used to detect new planets, both on the occasion of observations of other types of variability and as part of dedicated programs. In satellite programs aimed at searching for `the other Earth' (e.g. Kepler), the natural targets are solar type stars that emit little radiation in the UV part of the spectrum. Such stars can still be sources of UV radiation, because they have active chromospheres. Therefore, in analogy to the transits of the planet blocking part of the radiation coming from the visible stellar photosphere, we can expect the transits of a planet blocking UV radiation from the chromosphere (Sagiv et al. 2014). The detection of such phenomena would open a new window in the search of exoplanets. In addition, analysis of UV transits and modelling of the obtained light curves would allow us to study the chromospheres themselves, in particular to measure their depth. UVSat will be able to conduct uninterrupted observations of selected fields for up to 6 months, which will enable the detection of exoplanets with orbital periods of 60 - 90 days, for example, planets in the exospheres of low-mass stars. Statistical studies based on the results obtained with the help of Kepler indicate that the probability of detecting a candidate for a transiting planet with a size above 2 Earth radii is 0.55% (Borucki et al. 2011). This translates into one detection per about 200 monitored stars. Thus, UVSat has a chance to discover from a dozen to several dozen transiting exoplanets.

**Observational constraints:** Nearly all stars can be used to detect exoplanets using the transit method, although dedicated programs should focus rather on the relatively bright stars of the late spectral types. Such objects can be found both in the plane of the Galaxy and far away from it. For detection, precision of the observations (and therefore the largest possible aperture of the telescope) and relatively good time resolution (of the order of minutes) will be the most important.

## 3.15. Occultations by Kuiper Belt objects

Occultations of stars by the Kuiper Belt Objects (KBOs) allow discovering sub-km-sized objects, i.e. inaccessible by other methods due to their faintness. Therefore, only thanks to the occultations we can know the size and distribution of this population both in space and as a function of size. So far, it is not clear whether the distribution of small KBOs is similar to the observed distribution of traditionally discovered KBOs (approximated by the power law $N\ (r > 1\ \mathrm{km}) \sim r^{1-q}$, where $q \approx 4.5$ (Fuentes & Holman 2008; Fraser et al. 2008), because the effectiveness of the disruption of KBOs due to collisions is unknown. The registration of an occultation or obtaining restrictions on the density of the population of small KBOs requires observations of a large number of stars. In the last decade, there has been a great development of projects dedicated exclusively to such exploration. The upper limit obtained from the TAOS project (Zhang et al. 2008, 2013) made it possible to exclude some of the theoretically acceptable theoretical models of this distribution (Bianco et al. 2010). The latest results show, on the one hand, that the number of small KBOs seems to be large enough to explain the observed number of comets from the Jupiter family, on the other hand, indicates a deficit of sub-meter objects compared to a population of objects with diameters of 10 - 45 km. This deficit, in combination with theoretical modelling, suggests that small KBOs may be subject to significant erosion due to collisions taking place in the disk, which may be the result of the similarity of the Kuiper Belt and the dust disks observed around other stars.

**Observational constraints:** The much larger field of view of UVSat in comparison with the telescopes used previously for the searched of KBOs greatly increases the chance of detecting these phenomena. The KBOs search does not require a separate observational program, which is its great advantage, as it does not collide with any other project proposed for UVSat. However, the area extending up to ±30° in ecliptic latitude will be worth analysing in terms of searching for the occultations of star by KBOs.

### 3.16. Variability of comets, their rotational periods

Comets belong to the most variable objects of the Solar System. Their brightness changes both on a short and long time scales. The sudden, sporadic brightenings of comets are associated with outbursts, while regular changes in brightness are associated with the rotational period and the orbital period of the comet. In the case of seasonal orbital changes in brightness, the activity of the comet increases as it approaches the Sun, when the emission of gaseous and dust matter from its surface increases as a result of heating. In contrast, short-term changes in brightness are associated (a) with the reflection of sunlight by a rotating, non-spherical comet nucleus or (b) with changes in the surface activity. In the case of (a) the time series of photometric measurements should be made at large distances of heliocentric comets when the cometary nucleus is inactive. The amplitude of such brightness changes can be as high as 0.8 mag (Jewitt 1991). In the case of (b) the light curves will rather represent changes in emissions from the active area modulated by the angular distance of this area from the Sun; emission drops when the active area is on the night side in the 24-hour cycle. For comets belonging to the Jupiter Family Comets (JFCs) with an orbital period of about 6 years, potentially active areas occupy no more than 2 - 20% of the total surface area of  of cometary nucleus having a few kilometres in diameter. The amplitude of light variability associated with the active area is much lower than in the case of reflecting sunlight from the surface of the nucleus and tends to zero for the isotropic distribution of emission. With good spatial resolution of the active nucleus, the influence of the isotropic coma can be subtracted to obtain the brightness associated with the nucleus only. On the other hand, even for a very active comet, a series of photometric measurements can be used to determine the rotation period, if the activity changes are modulated by daily solar exposure. In particular, changes in brightness in the ultraviolet continuum may reflect changes in the structure of the nucleus activity during the daily cycle.

The determinations of comet rotation periods are rare; we know them for about 25 objects (Samarasinha et al. 2004), which is only a few per cent of comets known today. Rotational periods of comets fall within the range of several to several dozen hours. Knowing rotation periods for a statistically large sample of objects is important for the investigation of the nature of comets, by linking the rotational rate to activity, the size of the comet nucleus and the orbital period. In the recent years, it has been detected that the periods of rotation change over the orbital or shorter period, most likely under the influence of inhomogeneous gas and dust emission. Changes in the rotation period were confirmed for five JFC comets: 2P/Encke, 9P/Tempel 1, 10P/Tempel 2, 103P/Hartley 2, and 67P/Churiumow-Gierasimenko (Samarasinha & Mueller 2013, Keller et al. 2015); the rate of these changes is of the order of minutes per orbital period. However, in the case of the comet 103P/Hartley 2, the rotation period has changed by as much as two hours within three months (e.g. Belton et al. 2013). Changing rotation was also found for two single-appearance comets: C/1990 K1 (Levy) (Feldman et al. 1992) and C/2001 K5 (LINEAR) (Drahus & Waniak 2006). Studying rotational periods and their changes is important for understanding the physical evolution of comets.

**Observational constraints:** The study we propose should include measurements of brightness changes for comets that will be in the field of view of the instrument. In the case of a positive result, i.e. determining the rotation period of a given comet, it will be particularly important to repeat the measurements within a few months interval to detect the possible changes in the rotation period. The expected rotation periods have time scales of hours; hence the time resolution of minutes should be sufficient.

The study can cover both already known objects, and new ones if they have escaped dedicated sky surveys. In the first case, it will be possible to determine in advance whether any of the known comets will be in the field of future observations, and if so – determine precisely its ephemeris. Harder but also extremely interesting seems to be also a study aimed at discovering new objects of the Solar System, not necessarily comets, moving with respect to the observed stars.

## 4. Ranking table

The table below summarizes the information on the variability and location of the objects proposed for the studies with UVSat and an indication of the rank of the anticipated science for each of them. In the latter's assessment, the aspect of the uniqueness of UV observation, the significance for the entire astrophysics and the possibility of obtaining data for a significant number of objects of a given type were taken into account.

| Object or phenomenon | Time scale of variability | Variability range | Number in UVSat range | Location in the sky | Chapter | Rank |
|---|---|---|---|---|---|---|
| **Pulsating main-sequence stars** | hours | usually very small (mmag and sub-mmag) | large | vicinity of the Galactic plane | 3.1 | very high |
| **Be stars** | since hours to decades | usually below 0.5 mag, for pulsations, usually of the order of a few mmag or smaller | relatively large | vicinity of the Galactic plane | 3.2 | high |
| **Massive hot stars** | hours to years | diverse, from the order of a fraction of mmag (pulsating supergiants) to a few mag (LBVs) | small | vicinity of the Galactic plane | 3.3 | very high |
| **Massive binaries, including** | hours to days | relatively large (up to ∼1 mag) | a few dozen at least | vicinity of the Galactic plane | 3.4 | very high |
| **DPVs** | from 1 to hundreds days | a few tenths of mag | small | vicinity of the Galactic plane | 3.4.1 | high |
| **MXRBs** | from hours to many days | up to a few tenths of mag | small | vicinity of the Galactic plane | 3.4.2 | very high |
| **Intermediate and low-mass binaries** | minutes to days | up to a few mag | large except for LMXBs | mainly in the vicinity of the Galactic plane | 3.5 | average |
| **Chemically peculiar stars, including roAp stars** | minutes to days | usually below 0.1 mag, more frequently at the mmag level | a few hundred | mainly in the vicinity of the Galactic plane, but can be also found far from it too | 3.6 | average |
| **Symbiotic stars, including symbiotic novae** | from minutes (flickering) to years | up to several mag | a few dozens | mainly in the vicinity of the Galactic plane | 3.7 | average |
| **Cataclysmic stars, novae** | from a few seconds to dozens of days | up to a few mag | a dozen or so per year | the whole sky | 3.8 | high |
| **Early stages of supernova explosions** | from minutes to dozens of days | up to a few mag | at least a dozen per year | except the Galactic plane | 3.9 | very high |
| **Bright classical pulsators** | hours to dozens of days | up to a few mag | relatively high | Galactic plane (Cepheids), the whole sky (RR Lyrae stars) | 3.10 | average |
| **Pulsating compact objects** | from dozens of seconds to a few days | up to a few tenths of magnitude | a dozen or so | the whole sky | 3.11 | high |
| **Pre-main sequence stars** | hours to days | up to a few mag (FU Ori) or less (the other types) | a few dozens | star-forming regions | 3.12 | average |
| **Active galactic nuclei (AGNs)** | minutes to hundreds of fays | up to several mag, usually much smaller | at least a few dozens | except the Galactic plane | 3.13 | high |
| **Exoplanets** | minutes to hours (transits) | small, up to a few mmag | potentially very high | the whole sky | 3.14 | average |
| **Occultations of Kuiper Belt objects** | from fraction of a second to a few seconds | up to a few mag | a few per year (estimation uncertain) | the vicinity of ecliptic | 3.15 | high |
| **Comets** | minutes to dozens of days | up to 1 mag | occasional (moving objects) | the whole sky, but mainly the vicinity of ecliptic | 3.16 | average |

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