Research plan

Late stages of stellar evolution

Research area and previous work

Among the many new hot topics of astrophysics (high energy astrophysics, GRBs, AGNs, exoplanets etc.), stellar structure and evolution remains a major area in astronomy. There is particular interest in this research because the observational studies merely involve the widely applicable tools of classical astronomy, such as variable star observation and spectral analysis. Thanks to the development in the field, new types of variable stars are still discovered (e.g. Trimble & Aschwanden 2004; Kurtz 2006), which opens new avenues into studying evolutionary stages that were inaccessible in the past. Moreover, there are a number of unsolved problems and open questions in astrophysics that can be studied via variable stars (such as pulsating red giants, cataclysmic binaries and so on).

The astrophysics group at the University of Szeged has been working on pulsating variable star and eclipsing binaries for 20 years. In the last decade, we successfully extended our studies towards cataclysmic stars and star clusters, taking high-precision photometric and spectroscopic observations with large telescopes. We have established several collaborations with research institutes all around the world. Details of research activity are thoroughly summarized on our webpage (Szatmáry 2007).

In the past we were supported by the OTKA Grants T4330, T7522, F7318, T022249, F022259, T032258, T034615 and T042509. The last project – in which we have published 53 papers (35 in refereed journals and 18 in conference proceedings) with cumulative impact factor 150.5, and 43 independent citations for the time being - was finished in the middle of 2007. The purpose of the present proposal is to provide support for continuing and extending the research into new fields.

In this proposal we will focus on studying the late phases of stellar evolution. Our main goals are the followings:

1. Understanding stellar pulsations and period changes in giant and supergiant stars, analysing new observations and extensive data archives. The study of stellar evolution via pulsations. Application and development of time-frequency analyses. Photometry, infrared and optical spectroscopy of red giant stars.
2. Discovering new supernovae, photometric and spectroscopic monitoring of cataclysmic variable stars, determination of their distance, mass, luminosity and evolutionary state.

1. Pulsating variable stars

Measuring oscillations of a star is a beautiful physics experiment. Observing and modelling stellar pulsations (a process called asteroseismology) reveals physical parameters and inner structure of stars. This is a typical basic research, however, methods developed for analysing time-series observations (like time-frequency distributions) have a wide range of applications, including for instance, acoustics and medical sciences, so that there are practical aspects as well.

Our studies of stellar oscillations will focus on massive supergiant stars and pulsating red giants representing late evolutionary phases of low- and intermediate mass stars. The primary aim is to improve our understanding of physical phenomena with detectable effects on oscillations and evolution. An important goal is the determination of absolute physical parameters (mass, radius, temperature, luminosity, chemical composition) and evolutionary states of the studied objects.

Variable stars on the red giant branch represent late evolutionary phases of low- and intermediate mass stars and their pulsations are very difficult to study because of the typical periods ranging from tens to many hundreds of days. Building upon the expertise accumulated over the last 10-12 years (e.g. Szatmáry et al. 1994, 1996, 2003; Kiss et al. 1999, 2000; Kiss & Bedding 2003, 2004), we will continue research into red giant pulsations in two directions. On one hand, we will analyse decades-long visual light curves with time-frequency methods, in collaboration with the American Association of Variable Star Observers (AAVSO). This will allow modelling phenomena with the longest periods, up to few thousand days. On the other hand, we aim statistical asteroseismology of thousands of pulsating red giants observed by microlensing projects like MACHO and OGLE, i.e. physical parameter determination from statistical properties of large samples of pulsating stars. The latter will also include analysis of new photoelectric and CCD observations of bright field red giant stars.

This project will seek answers to the following questions:

- What kind of physical processes affect excitation mechanisms in red giants? In the last few years we found examples of chaotic and stochastic oscillations in Mira and semiregular variables (Kiss & Szatmáry 2002, Bedding et al. 2005, Kiss et al., 2006), which illustrated the strongly non-linear nature of processes within these stars. An important goal is to help found nonlinear asteroseismology, the discipline which allows physical parameter determination based on the characteristics of chaos.

- What drives the long-secondary periods in semiregular variables? One of the greatest mysteries of classical variable star astronomy is the presence of very long-term brightness fluctuations that can be observed in about 30% of all semiregular stars. The time-scale of this fluctuation is typically 10 times longer than the period of the radial fundamental mode, so that no regular radial oscillation can explain its occurrence (e.g. Wood et al. 2004, Derekas et al., 2006, Kiss L.L., Szabó Gy.M., Bedding T.R.: 2006). We will test currently existing hypotheses with time-frequency analysis of the best observed sample going back to 80-100 years in the AAVSO database, which is expected to yield strong constraints on most of the models.

- How can we separate evolutionary phases based on pulsation properties? We have recently shown (Kiss & Bedding 2003, 2004) that besides the Mira and semiregular variables on the Asymptotic Giant Branch, stars on the (first) Red Giant Branch (RGB) do also pulsate with periods of 10-50 days and amplitudes of 1-2%. The existence of distinct RGB-pulsations was so far demonstrated only in the Magellanic Clouds and here we aim the detection of these stars in other stellar systems (Milky Way, globular clusters). An important by-product of statistical asteroseismology was the application of pulsating red giants as tracers of galactic structure (Lah et al. 2005), which will be further improved for red giants in the Milky Way. In the case of post-AGB stars we pointed out the concordance of the predicted and detected position of the instability strip on the CMD (Kiss et al., 2007a), the second step will be the application for the Magellanic Cloud.

- Red supergiants are in a completely different evolutionary state, because these stars are young, massive and luminous objects that will explode as type II supernovae in the near future (in astronomical sense). A preliminary analysis of the best observed 50 red supergiants suggests that we can detect radial fundamental, first and second overtone modes, in agreement with the theoretical predictions. However, the modes are stochasticly damped. We plan to determine the relations between pulsations and physical parameters, with which we will be able to pin down the range of models that describe the stars better. If successful, this will also allow us to predict the time to the supernova explosion more accurately than is possible now.

- Mass-loss plays fundamental role in the evolution of red giants leading to the formation of extended circumstellar envelopes. We have a large number of medium-resolution near-infrared spectra (from multi-object spectroscopy with AAOmega on the Anglo-Australian Telescope, Kiss et al., 2007b) of more than 15000 southern red giant stars, and plan to acquire many thousands more. We will look for connections between mass-loss and the parameters of the stellar atmospheres (temperature, gravity, metallicity).

2. Astrophysics of supernovae and other cataclysmic variables

Massive stars end their life in violent explosion, as supernovae (SNe). Recently SNe became very popular in the astronomical literature, partly because Type Ia SNe turned out to be reliable distance indicators of cosmological distances that led to the discovery of the accelerating expansion of the Universe (Riess et al. 1998; Perlmutter et al. 1999). These SNe are thought to be originated from a thermonuclear explosion of a white dwarf in a binary system. Interestingly, such kind of binaries could also produce less destructive nova- or dwarf nova explosions. The progenitors of these cataclysmic binaries are very similar, but at present it is unknown what are the physical processes that lead to a supernova in one system and to a nova in another.

Meanwhile, core-collapse SNe (produced by the gravitational collapse of the iron core of a massive star into a neutron star) also gained particular attention after the identification of some of their progenitor stars (Hendry et al. 2005; Li et al. 2006). The mass of these progenitors turned out to be 8 - 10 solar masses, which was a major success for stellar evolution theory, since the theory predicted the same mass as a lower limit of core collapse. However, hydrodynamical models predicted much higher masses (up to 20 solar masses) for the same SNe. Such discrepancies may be solved by improving the distance measurements of SNe, since an erroneous distance plagues the measurement of all other physical parameters.

Type II SNe eject large amount of material, so the expanding gas envelope remains in the photospheric phase for months. The distance can be inferred by the Expanding Photosphere Method (EPM) that combines photometric fluxes, temperatures and expansion velocities to get the distance. The application of EPM for Type II SNe has been one of the main subject of our group recently (Vinkó et al. 2006; Takáts & Vinkó 2006).

In this proposal we intend to work on the following problems concerning SNe and other cataclysmic variables:

2.1. Supernova progenitors and their circumstellar environment

Massive, luminous stars interact with their circumstellar environment via episodic, and/or continuous mass loss processes. The shock wave produced by the supernova and the ejected envelope sweeps out this material, leading to radiation from X-ray to radio. We plan to study such interactions between SN progenitors and their environment using archival data of HST-, Spitzer-, Chandra-, and XMM-Newton telescopes. The X-rays emitted at early phases of the SNe (observed by Chandra, and XMM-Newton) are characteristics of dense circumstellar material, thus, these may prove high mass-loss rates prior to explosion. The IR radiation detected by Spitzer at late phases would indicate dust formation in the cooling ejecta, which is thought to play a major role in the dust production within the galaxy. The superb spatial resolution provided by HST would allow us to identify nearby companion stars, light echoes, or interstellar clouds that may help to reveal the evolution history of the exploded stars.

2.2. Discovering new supernovae with Baja Astronomical Robotic Telescope (BART)

SNe are unpredictable, transient events that occur practically randomly in space and time. They are searched for with dedicated telescopes that automatically monitor a number of target fields and compare the CCD frames taken at different epochs. The largest surveys, such as the SDSS Supernova Legacy Survey, concentrate on distant, faint galaxies at high redshift. There are a number of 0.5 m-class telescopes that target brighter, local galaxies, and discover 300 - 400 new extragalactic SNe per year. The newly installed Baja Astronomical Robotic Telescope (BART) offers a great opportunity for discovering such transient objects. It is a 50 cm telescope, it has a special optics with large field-of-view (FoV), and it is equipped with a professional 4k x 4k CCD resulting in an effective FoV of 40 arcminutes. This is much higher than the FoV of most of the other telescopes used for SN searching. We intend to develop the special control software for an automated SN-search program, and start to monitor a number of low-redshift galaxies accessible from Baja Observatory, Hungary. Our test measurements shows that the limiting magnitude of BART is roughly 18 (with Johnson V-filter, the unfiltered setup may reach 19 mag). With this equipment we are able to see/discover Type II SNe within 50 Mpc and Type Ia SNe within 100 Mpc. The follow-up observations of the new SNe are planned with larger telescopes, at Konkoly Observatory and abroad.

Our previous Galaxy Survey Program (OTKA T034615) contains 645 bright galaxies within 30 Mpc, and we have lots of previous CCD observations for these objects. This list will be extended up to 100 Mpc, and we intend to start observing the potential targets as soon as possible. Some minor extensions (including a filter wheel with wide-band Johnson and Gunn filters) and improvements on the telescope must be completed before this, but we expect to finish these during the first half of 2008.

2.3. UV-properties of Type II SNe from Swift data

The spectral properties of SNe in the ultraviolet are very poorly known, mostly because of the lack of observations. On the other hand, the UV-spectrum is very much affected by metallic lines even at the early phases, when the ejecta is the hottest and brightest. Thus, they may provide unique information on the physical conditions within the ejecta shortly after explosion. The NASA Swift space telescope (designed specifically for detecting/monitoring GRBs) is able to follow SNe in the 200 - 500 nm regime with its UV Optical Telescope (UVOT). Swift has a Target-of-Opportunity (ToO) program open for the astronomical community. We awarded telescope time in 2007 within this program and used Swift/UVOT to study the late-time spectra of SN 2004dj and its progenitor cluster (Vinkó et al., in preparation). We plan to continue this research, including new SNe, applying for the ToO-program and using the Swift public database.

2.4. Spectral modeling of Type II SNe with SYNOW

Understanding the physics of the expanding SN envelope needs complex physical modeling. We have already used the SYNOW code (Baron et al. 2000) for the interpretation of the emergent spectrum in the case of SN 2004dj (Vinkó et al. 2006). This program solves the radiative transport equation in the SN ejecta via the Sobolev approximation. In this proposed research we would like to further study this problem by seeking the solutions for these questions:

- what is the shape of the line source function in real SN atmospheres? Is the pure scattering case assumed in the code valid indeed?
- what is the optimal method for the determination of the expansion velocity at the photosphere?
- how could the code be refined to describe the hydrogen line profiles better?

2.5. Measuring cosmological distances with Type II SNe

The Expanding Photosphere Method (EPM) is a powerful tool for obtaining distances of supernovae. This is applicable mostly on Type II SNe, because the photospheric flux must be known from model calculations. Since these objects can be modeled much better than Type Ia SNe, EPM is based on a much more solid physical basis than the purely empirical distance measurement methods for Type Ia SNe. On the other hand, Type II SNe are fainter than Ia SNe, and EPM requires high S/N spectroscopy (for obtaining the expansion velocities). Thus, EPM in its present form is less suitable for faint SNe at high redshift. Our goal is to look for possibilities to extend EPM to cosmological distances. This would give us a unique opportunity to test the distance scale based on SNe Ia with a totally independent method, which would be very important for the verification of the accelerating expansion. Besides, the main physical parameters (envelope mass, nickel mass, luminosity, expansion velocity) of numerous Type II SNe could be computed from their new, refined distances, which would enable us to study the possible correlations among their parameters on a large, homogeneous sample.

2.6. Distance determination of classical novae with expansion parallax

A major difficulty in modeling nova explosions is the poor knowledge of distances, and, consequently, the total energy of the outbursts. Since 1999 we have been monitoring spectroscopically a few bright galactic novae, such as V1494 Aql, CI Aql and V4745 Sgr (Kiss & Thomson 2000; Kiss et al. 2001, 2004; Csák et al. 2005). In 2007-2010 the ejected gas shells of these novae are expected to reach diameters up to 0.5 - 2 arcseconds, which can be resolved with adaptive optics on large telescopes. We have already known the evolution of the expansion velocities (from optical spectra), thus, from the resolved angular diameters we could calculate the distances. From the distance we intend to estimate the total energy of the outburst, which in turn will yield information on the mass of the white dwarf.

Project realization and expected results:

Upgrading the instrumentation and adapting the computer systems of Szeged Observatory and Baja Observatory to the higher demands will happen in 2008-2009. We will carry out new observations with large telescopes abroad every year, while doing the analyses and publishing the results will be continuous. Because of the competitive telescope time allocation procedure, it is not possible to give a detailed schedule for the observations with large telescopes. However, the participants and/or collaborating researchers do have guaranteed telescope time and/or succesful proposal history for most of the aimed instruments, that makes our attached workplan feasible.

We expect 4-5 refereed journal papers in high-impact international journals every year. This means 16-20 papers during the proposed period. Beside the papers, we will also report our results at conferences, using all possible opportunities. Some of the results will be included into the PhD theses of those project participants who are expected to finish their PhD studies in the course of this proposal.

Participants:

7 researchers with PhD degrees in astrophysics (three as senior investigators), 4 young researchers (recently working on their PhD dissertation), 11 participants in total. In addition, 4 to 6 students of astronomy and PhD students will also be involved in the research work. They will join observations, data processing and publishing the results.

Equipments in Hungary which are planned to use for the observations related to the project

- Szeged Observatory, 40 cm Newton telescope with CCD camera and standard filters,
- Baja Observatory, two 50 cm robotic telescopes with CCD cameras and standard filters,
- Konkoly Observatory (Piszkéstető station), 60/90/180 cm Schmidt telescope and 1 m RCC telescope with CCD cameras and standard filters.

Equipments abroad which are planned to use for the observations related to the project

- Anglo-Australian Observatory, 3.9 m AAT. UCLES: high-resolution spectroscopy, AAOmega: medium-resolution multi-object spectroscopy with 400 objects per frame.
- Siding Spring Observatory 2.3 m telescope. CCD imaging and medium-resolution optical spectroscopy.
- Gemini Observatories, 8.1 m Gemini North and Gemini South telescopes. Imaging with adaptive optical facilities, multi-object spectroscopy.
- Mt. Hopkins Observatory, 6.5 m MMT. Adaptive optics, multi-object spectroscopy.
- Kitt Peak Observatory, 2.3 m Bok telescope. Deep, wide-field optical photometry and spectroscopy.
- FLWO 1.5 m: spectroscopy.
- Swift space telescope. Ultraviolet photometry of recent supernovae.

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