Stellar variability as a tool in astrophysics.
A joint research initiative in Austria

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Abstract

This brief contribution advertises some first results from an ongoing joint research initiative on stellar astrophysics in Vienna made possible by the Austrian Science Foundation. I present an overview of the individual projects by emphasizing their joint scientific strategy – i.e. using stellar variability to obtain information on astrophysical processes – and then focus on some recent results from the two projects dealing with stellar activity.

keywords: activity – pulsation – stellar evolution – starspots – Doppler-imaging

Meine Arbeit ist insofern nie ganz selbständig, als mein Interesse an einer Frage immer darauf beruht, daß andere eines daran nehmen.
Erwin Schrödinger

1 Introduction

Theoretical astrophysics in the outgoing twentieth century was and is dominated by a usually static approximation to highly dynamic phenomena as pulsations and starspots, the internal energy transport and the stellar structure, and even more so to the stellar core and its nuclear-reaction network and, inevitably, their evolution with time. However, the more detailed and the more precisely we are able to observe stars, the more they seem to be variable. A “constant” star is something that doesn’t exist. But how can we use the observable stellar variability and turn it into meaningful astrophysical information, and explain it with state-of-the-art theoretical models? As you might have guessed by now, this is not a straightforward task and is not foreseen to be completely and conclusively solved by the end of the “lifetime” of our projects.

The basic scientific driver of this joint research initiative is to contribute to and finally understand the complete stellar evolution of low-to-moderate mass stars, including our Sun. Because expertise and resources are of course limited in a small country like Austria, we focus on specific dynamic mechanism that, we think, are particularly important for certain parts of the stellar evolution but hadn’t been treated properly in the past.

These mechanism are:
• The collapse of the pre-stellar cloud and the appearance in the HRD,
• nuclear reactions of unstable, radioactive nuclei,
• stellar rotation, convection, and magnetic surface phenomena,
• radial and non-radial pulsations, and
• mass loss.

The related physical processes of these mechanism are dominating the observable stellar parameters in varying parts of the Hertzsprung-Russell diagram (HRD), other parts are driven by processes that we can not cover within our initiative, e.g. winds of massive hot stars or phenomena at the very low-mass end of the main sequence in general. Sometimes, for very special targets or groups of targets, several physical processes are mixed together, e.g. for the F-type γ Doradus stars with their non-radial pulsations and rapid rotation, and thus form a laboratory to also study border conditions. Such cases are important in order to find boundary lines and confine those parts in the HRD where a particular physical process is governing the stellar variability. Figure 1 are two H-R diagrams: one where pulsation-dominated regions are emphasized, and one where stellar activity dominates.

**Figure 1:** Left: H-R diagram for the pulsation domains showing the regions of g-mode, p-mode and radial (R) modes. The classical instability strip is indicated by the two inclined dashed lines and includes the Cepheid and RR Lyrae stars as well as the δ Scuti-, λ Boo-, and the rapidly-rotating Ap-stars (roAp). The γ Doradus stars are outside the instability strip but are, most likely, g-mode pulsators in the presence of convective envelopes. Right: The magnetic and acoustic-heating domains along with the usually refered boundary lines. The four shaded sections are areas where the dynamo might have different characteristics. (Latter diagram supplied by David F. Gray, University of Western Ontario.)

Observationally, we are thus focusing on, first, pulsating stars from the main sequence to the asymptotic giant branch (AGB) and even up to the “cool” central stars of planetary nebulae along with, second, investigations of stellar activity, caused not by pulsation, but stellar rotation and the dynamo-generated magnetic fields seen from pre-main sequence objects through red giants and horizontal-branch stars. From the theoretical side, the focus is on, first, the radiation hydrodynamics of radially pulsating stars and their dust-driven winds, second, the interpretation
of non-radial modes in terms of the internal stellar structure, third, on stellar
nucleosynthesis involving unstable nuclei and dynamical stellar evolution including
the collapse of the pre-stellar cloud, and, fourth, the transport of magnetic flux
tubes through stellar convective envelopes.

Since the space in this volume does not allow to present detailed results from
all the individual projects I will confine myself to mostly present their titles, the
principal investigators, a brief explanation that places them in context with the
above mentioned principal scientific goal, and one or two highlights. For those
readers who are more interested in actual results I add the URL of the various
home pages at the ASTROSERVER VIENNA where extensive lists of publications and
other material can be downloaded (partly in german and english).

2 The individual projects

2.1 Time-series stellar photometry with a robotic telescope
(P.I.: K. G. Strassmeier)

Within this project we acquired two 75cm automatic photoelectric telescopes (APTs),
placed them in a fully robotic observatory in southern Arizona and operate them
via the Internet from Vienna (Fig. 2). The telescopes now provide nightly narrow-,medium-, and broad-band photometry with high time resolution since November
1996. Main targets are rotating stars with starspots, non-radially pulsating δ Scuti-
, λ Bootis-, and γ Doradus-stars, the radially pulsating Miras and Semi-Regulars,
and some targets of opportunity such as VV Cephei and ε Aurigae. A description
of the telescopes and their operation procedure can be found in Strassmeier et al.
(1997) while nightly information on targets, status, and results is available on the
Web under

www.ast.univie.ac.at/~kgs/APT/.
2.2 Three-dimensional Doppler-imaging of stellar surface structure (P.I.: K. G. Strassmeier)

The technique of Doppler imaging enables us to indirectly resolve the stellar disk of a rotating late-type star and observe the changing temperature inhomogeneity due to cool starspots and their short- and long-term evolution. Figure 3 shows an example of our Doppler images of UZ Librae from March 1994. We believe that the short-term changes of the surface distribution of starspots are a fingerprint of the underlying transportation mechanism of magnetic flux tubes while its long-term changes are more related to the dynamo itself. By observing stars in various evolutionary stages we are able to follow the evolution of the dynamo efficiency throughout the HRD. Also, by observing in various heights of a stellar atmosphere we obtain crude three-dimensional images of stellar atmospheres. A list of related results and other information on the Doppler-imaging technique can be found on our “Stellar-Activity” homepage at

www.ast.univie.ac.at/~kgs/StellarActivity.html.

Figure 3: A Doppler image of the spotted K0-giant UZ Librae in 1994. The color-coded scale is temperature in Kelvin (dark means cool). Periodic variations of 12 high-resolution, high S/N, and phase-resolved spectra of three neutral spectral lines and 25 continuum points were used for their inversion. Adopted from Strassmeier (1996).

2.3 Asteroseismology along the central main sequence
(P.I.: W. W. Weiss)

Global stellar properties such as luminosity and radius can not, by themselves, strongly constrain the different models of internal structure and evolution. The measurement of multi-mode non-radial pulsations (nrp’s), however, can. This project focuses on main-sequence non-radial pulsations from solar-type stars to the slowly pulsating B stars, i.e. from convection driven to metal-opacity driven pulsations. It also includes the rapidly-oscillating Ap stars whose spectra are rotationally modulated
by an inhomogeneous surface abundance of chemical elements. These are likely related to the (primordial) magnetic field of these stars via a diffusion process. For more information see the “Asteroseismology” home page at

www.ast.univie.ac.at/~weiss.

2.4 Asteroseismology in the instability strip
(P.I.: M. Breger)

In general, the frequencies of normal $p$- and $g$-modes are strongly dependent on the parameters associated with stellar structure as a function of evolution, rotation, and magnetic field. To investigate this interplay between pulsational variability and internal structure one needs predominantly “normal” stars because of the complexity (compare with Fig. 4 as a representative example). The $\delta$ Scuti stars are excellent targets because they are not only located in the classical instability strip but also appear on and off the main sequence. However, the large amount of high and low frequencies requires the use of extensive photometric multisite campaigns with, e.g., our own Delta-Scuti Network or the Whole-Earth-Telescope. Current results include the finding of no detections of the theoretically predicted core modes for very evolved stars – explicitly for 4 CVn (P2III) – and conclude that there must be a presently undiscovered mechanism to stabilize or imprison core pulsation. Detailed information on past and future campaigns and their results can be found on the “Delta-Scuti-Network (DSN)” homepage under

dsn.ast.univie.ac.at/.

Figure 4: Asteroseismology of the $\delta$ Scuti star FG Virginis (A8V): A comparison of computed growth rates for $\ell = 0, 1, 2$ as a function of frequency agree with the observed frequency domain (24 frequencies detected; vertical dashes). The upper panel shows the asymmetry of the rotational splitting of the $\ell = 1$ (triangles) and the $\ell = 2$ (squares) modes.
2.5 Radiation hydrodynamics of pulsating stars  
(P.I.: E. A. Dorfi)

Simulations of non-linear radial pulsations by solving the full system of radiation hydrodynamic equations with convective energy transport on the one hand, and the use of a frequency-dependent radiative transfer code on top of the radial stellar structure on the other hand, connects the observations made in the other projects (and, of course, from the literature) to selfconsistent theoretical modeling. Currently, this project focuses on Cepheids, RR Lyrae, luminous blue variables, and AGB stars with special emphasis on dust-driven winds in Mira atmospheres. A typical example of a high overtone unstable pulsation is illustrated in Fig. 5 where a so-called strange mode instability leads to very rapid growth rates. See also the contribution by E. Dorfi in this proceedings. Again, further information may be obtained from the “Radiation HydroDynamics” homepage at

\[ \text{amok.ast.univie.ac.at/}. \]

![Graph](image)

**Figure 5:** The temporal evolution of a non-linear pulsation of a Hydrogen deficient Carbon (HdC)-star over 170 days with \( M = 1 \, M_\odot \), \( L = 10^4 \, L_\odot \) and \( T_{\text{eff}} = 6000 \, \text{K} \). 

a) The stellar luminosity in units of \( 10^4 \, L_\odot \).

b) The photospheric velocity in \( \text{km s}^{-1} \).

c) The radius of the photosphere in units of \( R_\odot \).

2.6 Stellar processes involving unstable nuclei and dynamical evolution (P.I.: H. Oberhummer, E. Dorfi)

A radiation hydrodynamical stellar evolution code is developed. At the end it will allow to calculate the static as well as the dynamical phases in a stellar life with the same numerical scheme. At the moment, an adaptive integration grid and a time-dependent nuclear reaction network has been applied to cloud-collapse simulations and succeeded to ignite deuterium burning of a one solar-mass cloud (cf. G. Wuchterl, see Splintermeeting on star formation). The current status of this work may be also viewed at

\[ \text{amok.ast.univie.ac.at/}. \]
2.7 Variability and mass loss on the AGB (P.I.: J. Hron)

Stars on the AGB are associated with three important phenomena: (1) Helium shell flashes accompanied by dredge up of nuclear processed material; (2) radial pulsations combined with the formation of shock fronts and (3) condensation of dust leading to the development of a stellar wind. This project provides the much needed observed mass-loss rates, atmospheric molecular cooling rates from IR bands, as well as isotope ratios from time-dependent model calculations as mentioned previously. Extensive use is made of the ISO satellite along with optical-, IR- and mm-spectroscopy and photometry (see the contribution by F. Kerschbaum, Splintermeeting on ISO). These data are accompanied by spectrum synthesis from hydrostatic and dynamic model atmospheres. First results include: (1) synthetic spectra based on dynamic models agree qualitatively better with ISO-SWS data, (2) we found no dependence of mass loss on the pulsational behavior in Irregulars and Semi-Regulaters (SR) similar to classical Miras, (3) photospheric velocities and Hipparcos luminosities favor overtone pulsation for SRs and fundamental mode for Miras. More about AGB stars in general and mass loss in detail may be found at www.ast.univie.ac.at/~fzi/AGB/agbwww.html.

2.8 Variable cool central stars of planetary nebulae (P.I.: M. Breger)

This project focuses on the “cool” (i.e. 35,000 K) central star of the planetary nebula IC 418, HD 35914, and consists so far of two photometric and spectroscopic campaigns with the “Delta-Scuti-Network (DSN)” of telescopes. We found two distinct kinds of variability: irregular light modulation with a time scale of days, as well as cyclic variations with a time scale of 6.5 hours. The latter, however, is not always strictly periodic and can not be reasonably explained by multiperiodicity; they appear to be semiregular. A possible cause might be the mixture of excited pulsation and wind variability. See also the “Global campaign” pages at the DSN home page at dsn.ast.univie.ac.at/dsn/ic418_94.html.

3 A more detailed excursion: stellar activity

The field of stellar activity clearly evolved from the solar-stellar connection proposed in the late sixties by Olin Wilson and colleagues because originally it simply meant a scaling-up of all the observed solar magnetic and dynamic phenomena. These phenomena include spots, plages, flares, prominences etc.. Today, however, we may observe stellar-activity phenomena that either have no counterpart on the Sun, e.g. polar starspots, or are qualitatively different, e.g. differential surface rotation in the opposite sense than on the Sun. On the other hand, recent successes in space-based solar physics brought us X-ray movies of the evolution and decay of active regions, of the velocity distribution beneath and on the surface of the Sun and, most recently, the propagation of a Moreton wave throughout the solar
atmosphere filmed by the SOHO spacecraft (Gurman et al. 1997). This has yet to be confirmed on other stars.

**Figure 6:** Two examples of the line profile variability due to starspots on a rapidly rotating star. The plusses are the observations and the corresponding lines are the Doppler-imaging fits. **Left:** UZ Librae, KOIII, $v \sin i = 67$ km s$^{-1}$, $P_{\text{rot}} = 4.7$ days (see also Fig. 3); **Right:** IN Virginis, K2IV, $v \sin i = 24$ km s$^{-1}$, $P_{\text{rot}} = 8.2$ days. Numbers denote rotational phase.

### 3.1 Line-profile variability and Doppler imaging

The drawback of the new solar-stellar connection is that we still can not resolve stellar disks, despite detecting features on a stellar surface. With the advent of Doppler imaging this has, at least partly and still indirectly, changed. See the reviews of Rice (1995) and Piskunov & Rice (1993). Figure 6 shows examples of observed spectral line profiles for two active K giants that indirectly lead to stellar surface structure with the equivalent resolution of 1 $\mu$-arc second.

An important further step of our Doppler imagery is the first image of a true solar-type star from high-resolution ($\lambda/\Delta \lambda = 120,000$) CFHT spectra and APT photometry: the single G1.5V-star EK Draconis (HD 129333). EK Dra has been an important target for investigating the evolution of stellar magnetism because it resembles the rapidly-rotating young Sun at the Pleiades age. From the inversion of a total of 12 different spectral lines we reconstructed several cool spots at low and medium latitudes, but the dominating feature is located consistently at a latitude of $\approx 70$--$80^\circ$, thus, far in excess where our Sun shows spots. In fact, our data indicate that this feature could be an appendage of a larger polar cap-like spot as seen on other rapidly-rotating stars. Spot temperatures between $\Delta T \approx 1200$ K and 400 K are recovered. This suggests that the Sun must have changed its dynamo mechanism between an age of $\approx 70$ Myr (Pleiades age) and its 4.5 Gyr today.

The map in Fig. 7 shows the unweighted average Doppler image of EK Dra from all spectral regions and intents to highlight the consistent details from the individual-line maps. We see that the “polar” spot at $b \approx 60$ -- $80^\circ$ and $\ell \approx 45^\circ$ is the most dominating feature while the weak spot at $\ell \approx 330^\circ$ is the least reliable of the spots that “survived” the averaging from the 12 lines.

We also applied an updated version of the MHD code of Schüssler et al. (1996) to generate trajectories of the rising (toroidal) flux tubes for a stellar model matching EK Draconis (for details see Granzer et al. 1997). The resulting stellar crossec-
Figure 7: A comparison of the average Doppler image of EK Dra in pseudo-Mercator projection (right panel) and a stellar model showing the meridional projection of trajectories of rising flux tubes and the predicted latitude distribution of emerging magnetic fields (very left graph).

tion in Fig. 7 can be directly compared with the Doppler image. But while the model predicts spots only between latitudes of 25–65°, with a preferred emergence at 30–35°, our Doppler image shows spots at significantly higher and lower latitude. Part of the discrepancy might be, e.g., with the poleward slip of loops already formed at very high latitudes but not taken into account in the models. Or, the dynamo might be of qualitatively different design as could be suspected by the rapid rotation of EK Dra when compared to the Sun.

3.2 Optical brightness variability

Another important sign of magnetic activity is its cyclic behavior. The solar 11 year sunspot cycle and the many detections in the Mt. Wilson (chromospheric) Ca II H&K program are the best examples. But what about photospheric, i.e. spot, cycles on other stars? Broad-band photometry, especially with a robotic telescope, is the ideal tool for such a long-term goal and is currently being conducted by one of our APTs in Fig. 2. Two examples, where we believe to have found a cyclic variability, are shown in Fig. 8. Their anticipated periods are on the order of the solar spot cycle. For one of these targets, El Eridani = HD 26337 (G5IV), we have also acquired Doppler-imaging data for meanwhile 10 consecutive years and will, eventually and hopefully, be able to construct a stellar butterfly diagram.

The main application of the APTs though, is to determine very precise rotation periods and their seasonal variations for about 100 spotted stars. Together with data from the literature this data base is then used to search for differential rotation (under the assumption that the period variations solely are due to the different latitudes at which spots appear). In this way differential rotation has been detected in many stars and is usually smaller than the comparable solar value by an order of magnitude. However, photometry can not tell us the sign of the differential rotation, i.e. do the poles or the equator rotate faster? Here, again, we employ time-series Doppler imaging and, for example, two cases where found that had
Figure 8: Long-term $V$ light curve variability due to starspots. Left: The evolved star Ei Eridani (G5IV); Right: The ZAMS star LQ Hya (K0V). A cyclic periodicity of around 10–12 years is anticipated. Note that the short-term variability is due to rotational modulation ($P = 1.945$ d for Ei Eri; $P = 1.6$ d for LQ Hya.) Adopted from Strassmeier et al. (1997).

higher latitude regions that rotate faster than the stellar equator; opposite to what is observed on the Sun, while yet others showed differential rotation similar to the Sun’s (see, e.g., Weber & Strassmeier 1998). Our current goal is to find out whether there is a relation between the amount of differential rotation, the existence of polar spots, and the stellar rotation period per se.

3.3 Rapid variability: the X-ray flares ...

At least since Einstein we know that huge X-ray flares with closed loops up to a height of several stellar radii occur on active stars. They have a direct, although dwarfed, analog on the Sun. The detection and determination of the extent of these loops is a key ingredient in the angular-moment evolution of late-type stars; shall it pre- or post-main sequence. X-ray flare light curves allow to determine the crude loop geometry through detailed modeling. In 1994 we were lucky to observe a huge flare on the active K giant HU Virginis using the HRI detector onboard of ROSAT (Fig. 9; Endl et al. 1997). The good coverage of the flare onset enabled us to apply a solar two-ribbon flare model and determine the energy budget and the geometry of the flare: latitudinal width of the flaring region was 30–60° on the stellar surface, the loop height was 1.0 stellar radii (5.9 $R_\odot$), and the event released $7.7 \times 10^{36}$ erg in the 0.1–2.4 keV bandpass of the ROSAT-HRI with a luminosity at flare peak of about 10 times the quiescent luminosity of HU Vir, or $10^5$ times the luminosity at solar maximum.

3.4 ... and corotating Hα prominences

Stellar prominences may be detected from the Hα-profile modulation when they sweep across the stellar disk and thereby eclipse parts of the stellar chromosphere. This is seen as an additional absorption transient moving across the line profile and can be used to backproject this 2-D information to a (pseudo) 3-D map with the height of the prominence as the spatial coordinate. The time that takes a prominence to cross the stellar disk can therefore be used to deduce the prominence height. This was pioneered in the late eighties by the work of Collier-Cameron &
Robinson (1989) and is being also pursued by Y. C. Unruh in Vienna. Recent observations (Fig. 10) of the rapidly-rotating star HE 520 in the young α Persei cluster showed the different velocities at which transients move through the line profiles at two different heights (seen as differently inclined dark stripes). Also shown are the profile deformations in the photospheric absorption lines of HE 520 (Fig. 10, right panel). Note the much slower crossing times of the photospheric (surface) features. Assuming stable corotating prominences, Jardine et al. (1998) computed their extent and found a range of heights between 2.8–5.1 stellar radii, which agrees with the corotating radius for this star.

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Figure 10: Rotational phase plotted against $v \sin i$ (in km s$^{-1}$) of the very young (50 Myr) α Persei star HE 520. The grey scale is line depth relative to the undisturbed profile (dark means additional absorption, white means pseudo emission). Left: Hα dynamic spectrum. Right: Photospheric dynamic spectrum. The inclination of the transients determines the distances of the prominences from the rotation axis. Courtesy Jardine, Barnes, Unruh & Collier-Cameron (1998).

References