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STELLAR SURFACE PHENOMENA: ROTATION, MAGNETISM, AND PULSATIONS

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RESUMEN

En esta revisión se resumen los fenómenos observados en la superficie y apenas sobre la superficie de estrellas calientes, particularmente los fenómenos que se relacionan con la rotación, pulsaciones y campos magnéticos. Gracias a los nuevos instrumentos y herramientas, por ejemplo satélites dedicados a la astrosismología (p.ej. CoRoT) y la nueva generación de espectropolarímetros (p.ej. Espadons en CFHT), nuestro conocimiento de estos fenómenos ha estado progresando muy rápidamente en los últimos años. Combinar estos resultados con los que se pueden obtener con interferometría proporcionará una vista global de los fenómenos superficiales estelares de las estrellas calientes.

ABSTRACT

In this review I summarize phenomena observed at the surface and just above the surface of hot stars, in particular phenomena related to the rotation, pulsations and magnetic fields. Thanks to new instruments and tools, such as satellites dedicated to asteroseismology (e.g. CoRoT) and the new generation of spectropolarimeters (e.g. Espadons at CFHT), our knowledge of these phenomena has been progressing very fast in the last few years. Combining these results with what can be obtained with interferometry will provide a global view of hot stars stellar surface phenomena.

Key Words: stars: activity — stars: atmospheres — stars: early-type — stars: magnetic fields — stars: oscillations (including pulsations) — stars: rotation

1. ROTATION

1.1. *Rapid rotation effects*

Among massive stars, Be and Bn stars rotate very rapidly. Be stars are non-supergiant O7 to A2 stars that displayed at least once Balmer line emission due to the presence of a circumstellar disk. Their rotation rate, however, is usually lower than the breakup rate. Bn stars are rapid rotators without disk, possibly the counterpart of Be stars without disk.

The rapid rotation of Be and Bn stars produces a flattening of the star, which can be observed in interferometry (e.g. α Eri, Domiciano de Souza et al. 2003). A gravity darkening effect, i.e. hotter brighter poles and a cooler darker equator, also occurs and can be observed in interferometry as well (e.g. Altair, Monnier et al. 2007).

1.2. *Rotational modulation*

Inhomogeneities at the surface of the star modulate observable spectroscopic and photometric quantities as the star rotates (see Figure 1). These inhomogeneities can be due to patches of chemical overabundances related to a magnetic field (see § 2.1).

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2. MAGNETIC FIELDS

Although the existence of magnetic fields in massive stars is no longer in question, our knowledge of the basic statistical properties of massive star magnetic fields is seriously incomplete. There is a troubling deficit in our knowledge of the scope of the influence of fields on massive star evolution, and almost no empirical basis for how fields modify mass loss.

Magnetic fields of massive stars are qualitatively different from those of low-mass stars because of their different internal structure. The origin of magnetic fields in massive stars is still debated but it could be fossil: the magnetic field is swept up during star formation, concentrated in the star and then produces a strong, slowly decaying stellar magnetic field which may survive well beyond the main sequence phase. Scenari based on dynamos or shear instabilities have also been investigated.

2.1. *Magnetic effects on the surface*

Magnetic massive stars often host a simple dipolar or possibly quadrupolar field. However, some massive stars (e.g. the B0 star τ Sco, Donati et al. 2006, 2008) display more complex magnetic fields.

Most of the time, the axis of the magnetic field is not aligned with the rotation axis of the star: the

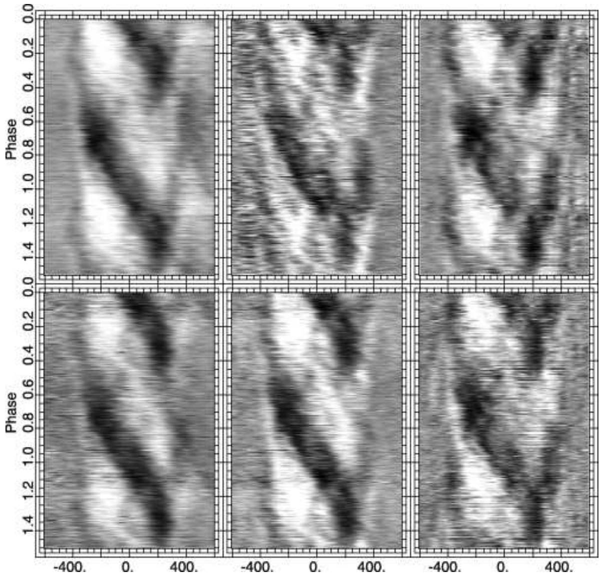

Fig. 1. Rotational modulation of the HeI line profiles of λ Eri with $P = P_{\rm rot}/2 = 0.702$ d (Balona et al. 2002).

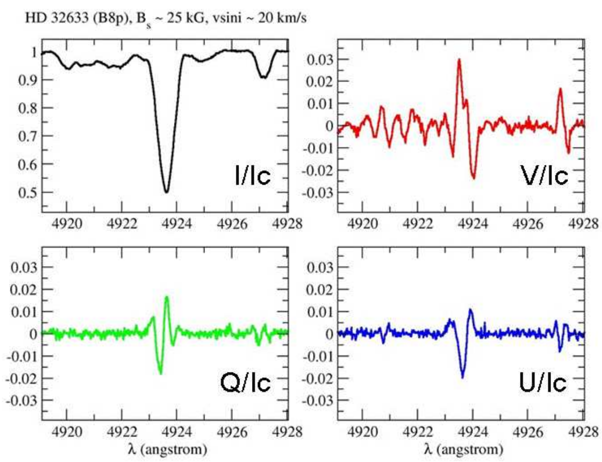

Fig. 2. Intensity of Stokes IQUV profiles of the B8p star HD 32633 as observed with Espadons at CFHT. Courtesy of J. Silvester.

dipole is oblique. As the star rotates, magnetic field structures, e.g. the magnetic poles, and structures linked to this field such as spots of chemical overabundances, produce observables variable with the magnetic/rotation period. In particular the Stokes profiles (see Figure 2) vary with the rotation period, and so does the intensity profile of the lines. Studying this variation allows to reconstruct the magnetic field topology at the surface of the star as well as the positions and sizes of patches on the surface via Zeeman-Doppler Imaging.

2.2. *Magnetospheres*

The effect of the magnetic field extends into the magnetosphere of the star. The rotation modulation related to the magnetic field topology and obliquity is then also observed in circumstellar quantities. In particular, the UV resonance lines sensitive to the stellar wind vary with the magnetic/rotation period. The study of these lines in the UV domain therefore allows to obtain information on the magnetic topology without measuring the magnetic field directly.

In addition, if the wind is confined by the magnetic field, X-ray emission is produced at the magnetic equator through shocks of particles coming from both magnetic hemispheres (Babel & Montmerle 1997). As the star rotates, the X-ray emission will also be rotationally modulated. The magnetic confinement of the wind can be characterized by the η_* parameter defined by ud-Doula et al. (2006): if $\eta_* > 1$, the wind is confined. For the star θ_1 OriC for example, predictions of a magnetically confined wind model reproduced the observed variable X-ray emission (Gagné et al. 2005).

The presence of a magnetic field and wind confinement does not allow to explain the presence of a Keplerian disk around Be stars. However, a field and wind confinement can produce a co-rotating disk or clouds, usually closer to the star than a Keplerian disk. Such co-rotating clouds have been observed in the Be star ω Ori (Neiner et al. 2003). Rigidly rotating magnetospheres have been modeled by Townsend & Owocki (2005). See Figure 3.

2.3. *MiMeS*

MiMeS (Magnetism in Massive Stars) represents a consensus effort by an international team aimed at investigating the magnetic field of massive stars. The basic aim of this programme is to exploit the unique characteristics of the new generation of spectropolarimeters to obtain critical missing information about the poorly-studied magnetic properties of these stars, to confront current models and to guide theory. See Wade et al. (2009).

The general scientific objectives are (1) to identify and model the physical processes responsible for the generation of magnetic fields in massive stars; (2) to observe and model the detailed interaction between magnetic fields and massive star winds; (3) to investigate the role of the magnetic field in modifying the rotational evolution of massive stars; and (4) to investigate the impact of magnetic fields on massive star evolution, and the evolution of the fields themselves. In particular, MiMeS explores the connection between magnetic fields of non-degenerate massive

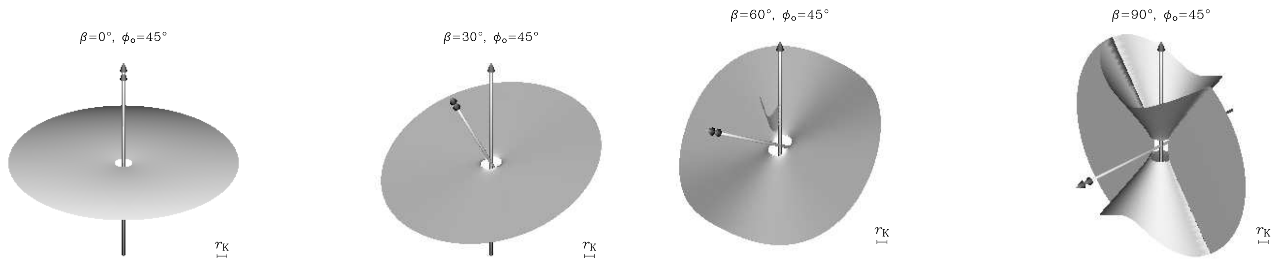

Fig. 3. Examples of magnetically confined wind model (Townsend & Owocki 2005).

stars and those of neutron stars, with consequential constraints on e.g. stellar evolution.

MiMeS has been awarded 640 hours of telescope time at CFHT (Canada France Hawaii Telescope) with the Espadons spectropolarimeter. Observations started in 2008 and will last until 2012. During the same period, observations will also occur with the Narval spectropolarimeter at TBL (Telescope Bernard Lyot), for a total number of hours similar to the Espadons programme.

3. PULSATIONS

3.1. *Type of pulsations*

Pulsations occur all over the upper end of the HR diagram. One can observe g-modes and mixed Rossby g-modes in SPB and Be stars, p-modes in β Cephei and Be stars, g-modes in supergiants, as well as strange modes or ϵ-driven modes in O stars.

Pulsation modes are characterized by 3 numbers: the degree of the mode l, the azimuthal order m and the radial order n. Modes with l=m=0 are called radial modes, with l=m≠0 sectoral modes, with m=0 zonal modes, and with l≠m tesseral modes.

Rapid rotation produces a deformation of the surface and new types of modes can appear: low-degree modes of island type which are equatorially focused, intermediate-degree modes which are chaotic, and high-degree modes of whispering gallery type (Reese et al. 2009).

Pulsations produce a deformation travelling along the line profiles as the star rotates. These deformations, although of low amplitude, can be observed in the spectra of massive stars and modeled (e.g. υ Cyg, Neiner et al. 2005).

The period of pulsations is different from the rotation period. Multi-periods can be observed associated with different modes.

3.2. *Beatings and Be outbursts*

In Be stars the presence of several modes of pulsations could lead to a beating effect and outburst: constructive interference of pulsation modes would

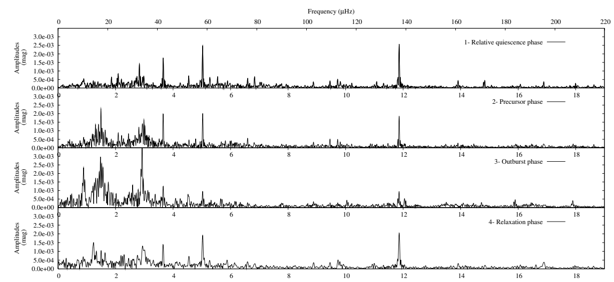

Fig. 4. Amplitude variation of the pulsation modes of HD49330 during the various phases of the Be outburst (Huat et al. 2009).

locally increase the velocity of the surface layer, help to reach the breakup velocity of the star, and then allow to eject material.

Rivinius et al. (1998) showed that indeed the maxima of amplitude of multiperiodic signals in the Be star μ Cen seem to coincide with the times of outbursts in this star. Such result, however, could not be obtained for any other star from the ground as it requires long-term multi-site high-precision observations.

3.3. *CoRoT*

The CoRoT satellite has been launched in December 2006 and provides high-accuracy high-duty cycle photometric data of stars covering the whole HR diagram. This includes massive stars and in particular Be stars.

HD49330 is a B0.5IVe star observed with CoRoT during 5 consecutive months and which underwent an outburst during the CoRoT run. The analysis of the CoRoT data shows that p-modes, present during the quiescence phase, decrease in amplitude during the precursor phase to reach minimum during the outburst and then increase again during the relaxation phase. On the opposite, g-modes start to appear during the precursor phase, their amplitude gets stronger at the time of outburst, and they disappear again after the outburst (Huat et al. 2009). The CoRoT data thus clearly show the correlation between pulsations and outburst (Figure 4). However, whether the beating of pulsations ignites the outburst or whether the outburst allows the appearance of g-modes and damps the p-modes still has to be investigated.

Cooler Be stars have also been observed with CoRoT and show multiperiods (Neiner et al. 2009; Gutierrez-Soto et al. 2009). The B8IVe star HD50209 shows only one intrinsic pulsation frequency and frequencies associated to the rotational splitting with $m = 0, -1, -2$, and -3 (Diago et al. 2009).

4. CONCLUSIONS

Rotation produces various effects that cannot be neglected: flattening, gravity darkening, and rotational modulation. Weak magnetic fields can be present in some massive stars and are associated with surface spots, co-rotating clouds, X-ray emission and UV variability. Pulsations are omnipresent in certain classes of massive stars, produce surface zones with different conditions and are related to Be outbursts. The study of these various phenomena brings important insights for stellar structure and evolution.

DISCUSSION

T. Szeifert: *You mentioned that for the B stars the dipolar field would typically dominate. Isn't this partly an observing bias since the dipolar fields are easier to detect in longitudinal B-field measurements?* — It is true that more complex fields are more difficult to detect because of the averaging of the field on the visible stellar hemisphere. Therefore we may obtain no detection instead of a complex field detection and thus miss the detection of some complex fields. However, the averaging would not make the field appear as dipolar, so there are indeed stars with mainly dipolar fields.

D. Gies: *Is it correct that g-modes could aid mass ejection from Be stars because they are characterized by larger horizontal velocity fields (that can add to rotational motion)?* — G-modes indeed have larger horizontal velocity fields than p-modes. They could thus help to reach the breakup velocity, if they are prograde. In addition, in rapidly rotating stars g-modes are concentrated at the equator where the velocity is already the closest to breakup, so g-modes are indeed good candidates to help to reach breakup.

W.J. de Wit: *How well determined is the mass in the case of the p+g mode modeling of* HD49330? — We determined the mass of HD49330 by fitting the spectra of this star with synthetic spectra. We obtained $M = 14.3 \pm 0.3\ M_{\odot}$. With such a high mass our preliminary models cannot excite g modes. We have to lower the mass well outside the error box to excite both p and g modes, even when using 2D rotational deformation. We are still working on this issue but a solution could come from enhancing the iron opacity bump for example.

H. Zinnecker: *Can you specify in more detail which important insights into the structure and evolution of massive stars your new observations have brought about?* — Our seismic models of rapidly rotating stars are still in a preliminary phase. However, we already see several important results emerge, in particular we found that we need extra (probably rotational) mixing to reproduce the observed frequencies and that the iron opacity bump may be enhanced. Results on weak magnetic fields also become more wide-spread thanks to MiMeS and the presence of a field brings constraint on evolutionary models.

D. Baade: *How do the attempts to model the CoRoT observations relate to the probable existence of outbursts and pulsations of Be stars in the Magellanic clouds?* — In the Magellanic clouds pulsations have been observed in Be stars even though models originally did not predict any due to the low metallicity of the environment. If the iron opacity bump is stronger than expected in the CoRoT galactic targets, maybe this is also true in the Magellanic clouds and pulsations would then be easier to excite.

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