Be star outbursts: transport of angular momentum by waves

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Abstract. The Be phenomenon, that is the ejection of matter from Be stars into a circumstellar disk, has been a long lasting mystery. In the last few years, the CoRoT (Convection, Rotation and planetary Transits) satellite brought clear evidence that Be outbursts are directly correlated with pulsations. We found that it may be the transport of angular momentum by waves or pulsation modes that brings the already rapid stellar rotation to its critical value at the surface, and allows the star to eject material. The recent discovery of stochastically excited gravito-inertial modes by CoRoT in a hot Be star strengthens this scenario. We present the CoRoT observations and modeling of several Be stars and describe the new picture of the Be phenomenon which arose from these results.

1. Be stars and the Be phenomenon

Be stars are Main Sequence or slightly evolved non-supergiant, late-O, B, or early-A stars that show or have shown emission in at least one Balmer line (Collins 1987). Emission can also appear in other lines of the spectrum as well as in the continuum, particularly as an excess of light in the infrared domain. The emission is due to the presence of a circumstellar disk, fed by episodic ejections of material from the surface of the star to a Keplerian orbit. This is called the “Be phenomenon”. However, how these outbursts producing the disk can occur was not understood until now.

There are ~2000 Be stars known as of today and listed in the BeSS (Be Star Spectra) database of Be stars (Neiner et al. 2011b). Be stars represent about 20% of all B-type stars in our galaxy. Only B stars of sufficiently high rotational velocity at the Zero Age Main Sequence (ZAMS) can become Be stars (Martayan et al. 2007), and this velocity depends on the metallicity of the protostellar environment. In addition, there seems to be a strong dependence of the proportion of Be stars compared to B stars as a function of spectral type. Indeed, the Be phenomenon is mostly observed around the sub-types B1-B2 (see, e.g., Fig. 1 of Balona 2000).

B2 is also the spectral type at which pulsations of both β Cep and Slowly Pulsating B (SPB) types can occur at the same time. Light and line-profile short-term variability (of the order of one day) due to non-radial pulsations is indeed detected from the ground
or with Hipparcos in almost all (86%) early-Be stars, in 40% of mid-types (B4-5e), and in only 18% of late-Be stars according to Hubert & Floquet (1998). Thanks to high-precision photometric space-based missions, we actually find that all Be stars pulsate, whatever their spectral type, but with a lower amplitude for cooler stars. Short-term variability also occurs owing to rotational modulation caused for example by surface spots.

Variability on other time scales is also common. Cyclic variations of the order of months or years are associated with the wind, which is variable and stronger than for B stars. In addition, variations in the disk emission line profiles with time-scales of a few years to decades are observed: first, the intensity of emission lines slowly decreases as the disk dissipates in the interstellar medium; second, a denser zone can exist in the disk, which slowly precesses and produces global one-armed disk oscillation. Finally, abrupt emission increases are due to short-lived (days, tens of days), sometimes recurrent, or/and long-lived (months) outbursts. Depending on the frequency of outbursts and on the speed of disk dissipation, the disk can sometimes completely disappear and reappear following a new outburst. For a complete review of Be stars, we refer the reader to Porter & Rivinius (2003).

Be stars are known to be very fast rotators. This leads to many rotational effects, in particular Be stars are flattened by the centrifugal force. However, their velocities are not high enough to reach the critical limit at which the centrifugal force compensates gravity at the equator. Indeed, galactic Be stars rotate on average at 88% of the critical angular velocity (Frémat et al. 2005). Thus, at least in most cases, while rotation is certainly an important ingredient in igniting outbursts, it cannot by itself explain the ejection of matter from the star that leads to the formation of the decretion disk. Another mechanism is required to provide the additional angular momentum at the surface needed to eject matter.

Several explanations have been put forward to provide this additional angular momentum. Oudmaijer & Parr (2010) showed that about 30% of Be stars are in binary systems with a close companion, which is similar to the binary rate of B stars. The binary companion certainly plays a very important role for those 30% of Be stars (e.g., in Be/X-ray binaries). For single stars, results from the MiMeS project (e.g. Neiner et al. 2011a) showed that the magnetic field of Be stars, if it is present, is weak, and that it only influences possible co-rotating clouds close to the stellar surface and not the Keplerian Be disk (Neiner et al. 2012b). Therefore pulsations appear to be the most likely explanation, in addition to the rapid rotation, of the Be phenomenon.

2. Correlation between pulsations and outbursts in HD 49330

CoRoT allowed us to observe the hot (B0IVe) Be star HD 49330 during an outburst (Huat et al. 2009). By completing a photometric analysis of the precise CoRoT data of that star acquired over ~136 days, we were able to detect over 300 different frequencies attributable to variations, including at least thirty independent ones. These include high frequencies as well as several groups of low frequencies, which are typical of the pressure (p) and gravity (g) pulsation modes observed in β Cep and SPB stars, respectively. Some of the frequencies have also been detected in photospheric line profile variations with the help of simultaneous spectroscopic observations (Floquet et al. 2009).

Thanks to these CoRoT data, we have discovered a correlation between both amplitude changes and the presence/absence of certain frequencies of pulsation, with the
different phases of an outburst: (i) the amplitude of the main p-mode frequencies decreases before and during the outburst and increases again after it; (ii) several groups of g-mode frequencies appear just before the outburst, their amplitude reaches a maximum during the outburst, and they disappear as soon as it has finished. These frequencies appear to have complex structures, which could represent pulsation modes with a short lifetime.

The detailed characterization of the pulsation modes and fundamental stellar parameters of HD 49330, and the presence of both p-modes and g-modes, provide strong constraints on its seismic modeling. We tried to model HD 49330 with $\kappa$-driven pulsations using the Tohoku oscillation code (Saio & Cox 1980; Lee & Baraffe 1995) that accounts for the combined action of Coriolis and centrifugal accelerations on stellar pulsations as needed for Be star modeling. However, whatever models of pulsations and stellar structure we used, we find that p-modes and g-modes cannot be excited at the same time by the $\kappa$ mechanism in HD 49330 using stellar parameters determined spectroscopically.

3. Discovery of stochastically excited gravito-inertial modes in HD 51452

HD 51452 is a hot Be (B0IVe) star observed with CoRoT, which has a rotation frequency $f_{\text{rot}} \sim 1.22 \, \text{c d}^{-1}$. For such a hot star, the $\kappa$ mechanism can create p-modes of pulsations or possibly low-order g-modes with frequencies above $\sim 1.5 \, \text{c d}^{-1}$. Nevertheless g-modes are detected in the CoRoT light curve of HD 51452 with frequencies below $\sim 1.5 \, \text{c d}^{-1}$. In addition, a multiplet of frequencies is detected, with its main peak in the domain below $\sim 1.5 \, \text{c d}^{-1}$, with a frequency spacing of about $0.6 \, \text{c d}^{-1}$ (see Neiner et al. 2012a). These frequencies below $\sim 1.5 \, \text{c d}^{-1}$ cannot be explained with the $\kappa$ mechanism, even when taking stellar flattening into account. They could, however, be stochastic gravito-inertial (gi) modes. In particular sub-inertial gi-modes would be below $\sim 2.44 \, \text{c d}^{-1}$.

There are two types of gi-mode: (1) those usually called g-modes, which are gravity modes modified by the Coriolis acceleration, and which show a regular pattern in period when they are asymptotic (Lee & Said 1997; Ballot et al. 2010), and (2) rotational (r) modes, which are mainly driven by the Coriolis acceleration, are sub-inertial and show regular patterns in frequency (Provost et al. 1981; Saio 1982; Lee 2006). Since we observed at least one multiplet in frequency in the sub-inertial domain for HD 51452, those peaks may be interpreted as r-modes. Since no specific frequency or period spacing is found for the other frequency peaks, they could be any type of gi-mode.

Convective regions, such as the convective core and the sub-surface convection zone in massive stars, are indeed able to stochastically excite oscillation modes (Cantiello et al. 2009; Belkacem et al. 2010) and particularly g-modes (Samadi et al. 2010; Shiode et al. 2013). The latter become gi-modes in fast rotators such as HD 51452 because of the action of the Coriolis acceleration (see e.g. Lee & Said 1997; Dintrans & Rieutord 2000; Mathis 2009; Ballot et al. 2010). This excitation is also observed in realistic numerical simulations of convective cores surrounded by a stably stratified radiative envelope (see Browning et al. 2004). Gravito-inertial waves are excited through their couplings with volumetric turbulence in convective regions (where pure g-modes in a slowly rotating star are evanescent, while gi-modes in a rapidly rotating star become inertial) and by the
impact of structured turbulent plumes at the interfaces between convective and radiative regions.

Samadi et al. (2010) examined the stochastic excitation of gravity modes by turbulent convection in massive stars. They found that the excitation of low $n$-order g-modes occurs in the core while the asymptotic g-modes are mostly excited in the outer convective zone. The mode amplitudes that they deduced, however, are well below the detection threshold of the CoRoT satellite for a massive star. On the contrary, recent work by Shiode et al. (2013) showed analytically that taking stochastic excitation by penetration into account produces g-modes of detectable amplitude. In both works however, no rotation is considered. In addition, three-dimensional (3D) simulations of a convective core in a A star (Browning et al. 2004) or B star (Augustson et al., in preparation) showed efficient stochastic excitation of g-waves.

HD 51452 is a Be star, rotating close to its breakup velocity. Therefore, the calculation of the excitation of gi-modes (including r-modes) in this star requires the study of the influence of very fast rotation. This application can be derived from the work by Belkacem et al. (2009) and is the study of a forthcoming paper (Mathis et al. 2013). The detection of gi-modes in HD 51452 presented in Neiner et al. (2012a), however, already suggests that fast rotation enhances the amplitude of gi-modes and thus r-modes.

The fact that HD 51452 is a very hot Be star excludes the possibility that the observed gi-modes are excited by the $\kappa$-mechanism. In view of these results, however, it might be necessary to reconsider our interpretation of several other rapidly rotating B or Be stars, for which the $\kappa$-mechanism seemed like an obvious excitation mechanism but for which stochastic excitation might also be at work. In particular the g-modes observed in HD 49330 (see Sect. 2) could be stochastically excited, which would explain why the seismic models with $\kappa$-driven modes did not work.

4. Transport of angular momentum by waves in Be stars

Considering the arguments presented above for HD 51452, the results of our modeling of HD 49330 with the $\kappa$-mechanism, as well as the fact that the power spectrum of that star shows broad frequency groups rather than sharp frequency peaks around 1-2 c d$^{-1}$ (Huat et al. 2009), we propose that HD 49330 hosts stochastic g-waves.

During the quiet phase, stochastic gi-waves can be excited in the convective core. If they are sub-inertial, as observed in the Be star HD 51452, these waves transport more angular momentum to the subsurface layers than $\kappa$-driven modes because their frequency is lower. The net deposit of angular momentum indeed depends on the thermal dissipation, i.e., it is proportional to $1/f^4$ for a given rotation (Zahn et al. 1997; Mathis 2009). When enough angular momentum has accumulated in the outer layers of the star, these layers get unstable and could emit transient g-waves, which we detect. Possibly, the g-waves excited in the core may then also become visible. The surface layers reach the critical velocity, in particular at the equator where the rotation was already the closest to critical. The destabilisation of the surface layers thus ignites the outburst and breaks the cavity in which the p-modes were propagating. This explains both the disappearance of the p-modes during the precursor and outburst phases of HD 49330 and the ejection of material from the surface into the disk, i.e., the occurrence of the outburst, as observed by Huat et al. (2009) with CoRoT. Relaxation then occurs, recreating the cavity and letting the p-modes reappear while the transient g-waves disappear.
Each time stochastic g-waves from the core accumulate enough angular momentum in the outer layers of the star, this outburst phenomenon will occur again.

The idea that non-radial oscillations excited in massive stars are able to efficiently transport angular momentum and to allow the surface of a Be star to reach its critical velocity has already been proposed by Ando (1986), Lee & Saio (1993), and Lee (2006). However, in these previous works, gi-waves were excited by the \( \kappa \)-mechanism. In the case of HD 49330, we propose that gi-waves are stochastically excited in turbulent convective regions. Pantillon et al. (2007) and Rogers et al. (2012) demonstrated that stochastic gi-waves are able to transport angular momentum in the same way as \( \kappa \)-driven waves. The type of excitation does not influence the transport. It depends mostly on the amplitude and frequency of the mode (Zahn et al. 1997; Mathis 2009). The higher the amplitude and the lower the frequency, the more transport there is.

The Tohoku models of HD 49330 indeed show that the rate of local angular momentum change due to pulsational transportation integrated over the mean sphere increases drastically in the few percents of the stellar radius just below the surface, i.e., there is a strong net deposit of angular momentum in the surface layers, because this is where the pulsations are damped. This confirms that pulsations increase angular momentum in the outermost layers of the star.

The Tohoku pulsation code is currently being modified to include stochastically excited pulsations. This new version will be used to test our scenario (Neiner, Saio et al., in preparation).

5. Conclusion

All Be stars observed with CoRoT pulsate, whatever their spectral type. A scenario similar to the one observed in HD 49330 could thus occur in all other Be stars, thus providing an explanation of the long-lasting mystery of the origin of Be outbursts and disks, for single Be stars.

Stochastic waves are certainly excited in the convective core of any massive star, but with amplitudes that may be undetectable (even with space-based facilities) if the star rotates slowly. From the observations of stochastically excited gi-modes in HD 51452 and the results of the seismic modeling of HD 49330, we however propose that rotation enhances the amplitude of stochastic gi-waves/modes. Since these waves are of low frequencies, they transport more angular momentum than other waves/modes of higher frequency for a given amplitude. Therefore we conclude that a hot slowly rotating pulsating B star will only excite detectable \( \kappa \)-driven p modes, i.e., it will be a \( \beta \)Cep star, but if it rotates fast, it will also excite stochastic gi-waves/modes with a larger amplitude than the \( \beta \)Cep star and it will become a hot Be star. A cool slowly rotating pulsating B star will excite \( \kappa \)-driven g-modes, i.e., it will be a SPB star, but if it rotates fast, it will also excite stochastic gi-waves/modes with a larger amplitude than the SPB star and it will become a cool Be star.

We conclude that single Be stars bring their surface layer above the critical velocity thanks to three ingredients: (1) rapid rotation itself, (2) the transport of angular momentum by pulsations (of all types, but mostly prograde g-modes), and (3) the enhancement of the amplitude of stochastic gi-waves thanks to the rapid rotation, which allows more transport of angular momentum. The fact that a B star becomes a Be star therefore depends strongly on its rotation rate, pulsations, and convection (in competition with its stellar wind).
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