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Making a Be star: the role of rotation and pulsations

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Abstract. The Be phenomenon, i.e. the ejection of matter from Be stars into a circumstellar disk, has been a long lasting mystery. In the last few years, the *CoRoT* satellite brought clear evidence that Be outbursts are directly correlated to pulsations and rapid rotation. In particular the stochastic excitation of gravito-inertial modes, such as those detected by *CoRoT* in the hot Be star HD 51452, is enhanced thanks to rapid rotation. These waves increase the transport of angular momentum and help to bring the already rapid stellar rotation to its critical value at the surface, allowing the star to eject material. Below we summarize the recent observational and theoretical findings and describe the new picture of the Be phenomenon which arose from these results.

Keywords. stars: emission-line, Be, stars: mass loss, stars: oscillations (including pulsations)

1. Stochastic excitation of pulsations in Be stars

Be stars are massive stars with a decretion disk that are known to pulsate thanks to the κ mechanism. The correlation between pulsations and the ejections of matter into the circumstellar disk was first proposed by Rivinius *et al.* (2001) and firmly established by Huat *et al.* (2009) thanks to *CoRoT* observations.

Sub-inertial gravito-inertial modes (below twice the rotation frequency) have recently been detected in the early Be star HD 51452 with *CoRoT* (Neiner *et al.* 2012). These modes cannot be excited by the κ mechanism usually invoked for those stars, because HD 51452 is too hot (B0 IVe) to be in the κ-driven g-mode instability strip. Since the observed modes have very low frequency and a short lifetime, we have proposed that they are excited stochastically in the convective core and at its interface with the surrounding radiative envelope.

In addition, low-frequency g modes have been observed with *CoRoT* in another early Be star, HD 49330, during an outburst (Huat *et al.* 2009). We propose that these modes are also stochastically excited, as suggested by their short lifetime. Indeed, these modes are only visible during the outburst, while the κ-driven p modes get destabilized during the outburst. However, in this case, the stochastic modes we observed are probably those excited just below the surface during the outburst rather than the ones excited in the convective core.

It was not expected that stochastically excited gravito-inertial modes could be observed in massive stars (Samadi *et al.* 2010). However, Be stars are very rapid rotators and stochastic excitation is enhanced in the presence of rapid rotation, through the Coriolis acceleration which modifies gravity waves. This has been demonstrated analytically by Mathis *et al.* (2013) and observed in numerical simulations by Rogers *et al.* (2013) (see also Browning *et al.* 2004). Indeed, in the convective zones, when rotation is rapid, gravity modes become less evanescent in the super-inertial regime and propagative inertial modes in the sub-inertial regime.

Such stochastic modes are thus probably present in all rapidly rotating massive stars. Therefore, in the case of rapid rotators, the identification of low-frequency modes should be considered carefully and not systematically attributed to the κ mechanism as has been done until recently.

2. Transport of angular momentum from the core to the surface

Lee (2013) showed that gravito-inertial modes excited by the κ mechanism transport angular momentum and could play a role in the Be phenomenon. However, in the sub-inertial regime, the transport of angular momentum was believed to become less efficient because of gravito-inertial waves equatorial trapping (Mathis *et al.* 2008, Mathis 2009). Our recent work shows that transport by trapped sub-inertial waves may be sustained in rapidly rotating stars thanks to the stronger stochastic excitation by turbulent convective flows. Moreover, sub-inertial gravito-inertial modes have very low frequencies and therefore they transport more angular momentum than modes with higher frequencies.

We thus propose that this mechanism allows to transport angular momentum from the convective core of Be stars, where sub-inertial gravito-inertial modes are excited, to their surface. The accumulation of angular momentum just below the surface of Be stars increases the surface velocity. The surface then reaches the critical velocity so that material gets ejected from the star.

3. Conclusions

Thanks to the discovery of stochastically excited gravito-inertial modes in the hot Be star HD 51452 and to the observation of the correlation between these pulsations and a Be outburst in HD 49330, both with the *CoRoT* satellite, we have shown that stochastic gravito-inertial waves play an important role in Be stars. We demonstrated analytically that it is rapid rotation that enhances those modes in Be stars. This is also confirmed in numerical simulations. Since sub-inertial gravito-inertial modes efficiently transport angular momentum, we propose that they could be the key to the Be phenomenon, i.e. to the ejection of material from the surface of Be stars into a circumstellar Keplerian disk.

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