The Variable Ca II Absorption in β Pictoris during 1998

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Abstract

Variable absorption features were observed in the visible and ultraviolet spectrum of β Pictoris soon after this star gained attention in the early 1980s due to its large IRAS infrared excess and the discovery from optical imaging of an edge-on dust disc. The absorption has been attributed to the evaporation of infalling planetesimals or comet-like bodies (the Falling Evaporating Bodies, or FEB, hypothesis). With a view to confronting this hypothesis with fuller observations, we monitored the Ca II H & K lines in β Pictoris simultaneously during 1998, obtaining sequences of spectra on 50 nights. Variable absorption was usually present. The different oscillator strengths of the H & K lines permit the determination of covering factors, but detailed modelling is required to test whether all features can be explained by the FEB hypothesis. The blend of Ca II H with Balmer Hε means that the H & K photospheric profiles are different and that the variable absorption features do not evolve in parallel. The behaviour of the variable absorption on November 27 is evocative of a body passing in front of the stellar disc in a prograde equatorial orbit.

Keywords: circumstellar matter — line: profiles — stars: individual (β Pictoris)

1 Introduction

Attention was drawn to the bright, southern A5 V star β Pictoris by its large IRAS infrared excess. Imaging soon revealed that β Pictoris is surrounded by an edge-on dust disc extending over 1 000 AU from the star. Spectroscopy revealed the presence of circumstellar absorption features, some of which are variable with velocities up to a few $\times 10^2$ km s^{-1} in both low-ionization species such as Ca II and high-ionization species like Al III and C IV. It is believed the system may be a transitional object between a young star surrounded by a proto-planetary disc and more-evolved systems where giant planets (at least) have formed. Recent reviews include those by Artymowicz (1997) and Vidal-Madjar, Lecavelier des Etangs & Ferlet (1998).

1.1 The FEB hypothesis

The variable absorption features have been ascribed to material evaporating from planetesimals or comet-like bodies on star-grazing orbits. This 'Falling Evaporating Bodies' (FEB) hypothesis has principally been developed by workers in Grenoble (e.g. Beust et al. 1998 and references therein). The FEB model explains several observed phenomena. For example, shocks can produce the Al III and C IV ions not expected from photoionization by an A5 V star, and lower-velocity absorption

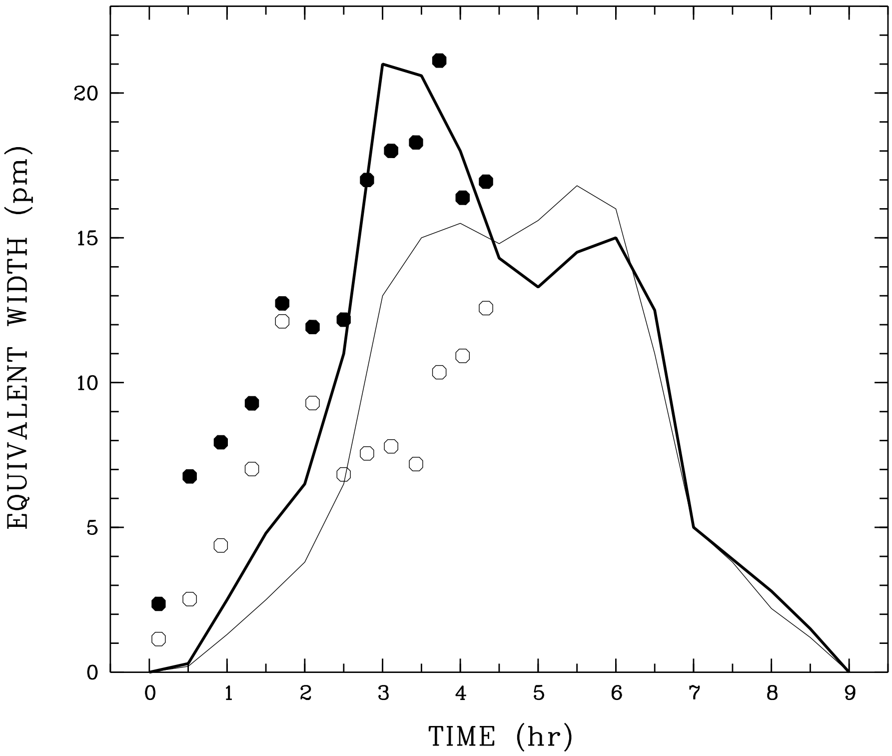

Figure 1: The predictions of Beust & Lissauer (1994) for the prograde, equatorial passage of an FEB across the disc of β Pictoris (their Figure 7). Bold line: evolution of Ca II K. Narrow line: evolution of Ca II H. The closed and open circles are our K and H observations of the $\sim$120 km s^{-1} feature on 1998 November 27, arbitrarily offset in abscissa and arbitrarily scaled in ordinate to emphasize the similarity in form, as explained in Section 2.2.

features are longer-lived than higher-velocity ones because the FEB crosses the line of sight further from the star. However, puzzles remain, such as the extended lifetimes of lower-velocity features (possibly attributable to an infalling stream of FEBs) and the comparative rarity of blue-shifted features, which may be indicative of the presence of planetary resonances perturbing FEBs from circular into star-grazing orbits at selected azimuths. The behaviour of the variable absorption requires better observational characterization.

1.2 The Ca II H & K absorption

The Ca II H & K absorption lines have different oscillator strengths (that of K is twice that of H) and this makes it possible to determine the optical depth of the obscuring ionic cloud, $\tau_{\rm K}(= 2\tau_{\rm H})$, and the fraction α of the stellar photosphere that it covers. Under the crude model of a uniform cloud and photosphere, these parameters are obtained simply by solving the equations for the line depths, $p_{\rm K} = \alpha(1 - e^{-\tau_{\rm K}})$ and $p_{\rm H} = \alpha(1 - e^{-\tau_{\rm K}/2})$, whose observed values should fall within the limits $p_{\rm H} = \frac{1}{2}p_{\rm K}$ (optically thin) and $p_{\rm H} = p_{\rm K}$ (optically thick). Simple analyses of this sort have shown that the covering factors, α, are smaller for higher-velocity features, as expected if radiation pressure close to the star inhibits expansion of the cloud of Ca$^+$ ions.

In reality, the physical situation is more complicated. The photosphere is limb darkened, so an ionic cloud of a given size blocks proportionately more light when its projected location is closer to the centre of the stellar disc. More importantly, the photosphere is rotating fast ($V \sin i \simeq 140$ km s^{-1}). Since the FEB absorption is detected against the spectral background of the photospheric Ca II lines, whose profiles are a strong function of wavelength, the intensity of the photospheric light at any wavelength and at any point on the projected stellar disc is altered because of rotational Doppler shifts. A concrete example will make this clearer. If planetary perturbations cause planetesimals to become star-grazing, the FEB orbits are likely to be equatorial. The photospheric K profile increases in intensity away from its central wavelength. An FEB located in front of either the blue- or the red-shifted equatorial limb will therefore experience enhanced flux at the central wavelength of the absorption compared to what is would experience if the star was not rotating. Because of blending, however, the profile of the photospheric H line in β Pictoris is *not* symmetric about the wavelength corresponding to the atomic transition. The intensity initially *decreases* on the long-wavelength side, where it is blended with Balmer $H\varepsilon$. An equatorial FEB therefore experiences enhanced intensity if it is located in front of the approaching limb, and reduced intensity if it is located in front of the receding limb. As Beust & Lissauer (1994) and Hubeny & Heap (1996) realised, the joint evolution of the differently-behaving H & K absorption features should permit tracking of the passage of FEBs across the stellar disc and thus provide further evidence for the FEB hypothesis. Figure 1 shows predictions from Beust & Lissauer for the prograde, equatorial passage an FEB of a certain size and orbit; it is even possible for the H line to be stronger than the K line, despite its weaker oscillator strength.

1.3 Previous observations

Observations of the Ca II lines in β Pictoris are thus of great interest, and intermittent échelle spectroscopy of this star has been underway from the Mt John University Observatory (MJUO) since 1992, sometimes as part of multi-observatory campaigns. Results from 1992 December have been published by Lagrange et al. (1996); data from 1994–96 (intensive during 1995) have been presented by Petterson & Tobin (1999). For these observations, the detector was too small to capture both the H and K lines, which were therefore observed sequentially, but difficulties arise in their joint interpretation because the absorption can evolve over the same timescale as required to obtain a spectrum. For this reason a spectrograph focal reducer was built (Tobin et al. 1998) and a larger CCD detector acquired in order to permit simultaneous observations of the H & K lines. A two-year programme of intensive monitoring began in 1997 (Persson 1998).

2 The Ca II absorption in 1998

2.1 New observations

The McLellan One-metre Telescope at MJUO was allocated to this research over 45 full and 39 shared nights during 1998. We were able to acquire 407 sets of spectra during 178 hours of observation on 50 nights between 1998 January 20 and December 2, where the southern declination of this star allows year-round observation. Reduced spectra were normalized by absorption-free photospheric profiles to isolate the circumstellar features, which, following earlier workers, we were able to well-fit with multiple Gaussian profiles. (We fitted a common velocity and width but separate depths and hence equivalent widths to corresponding H & K features.) For fuller details, see Barnes (1999).

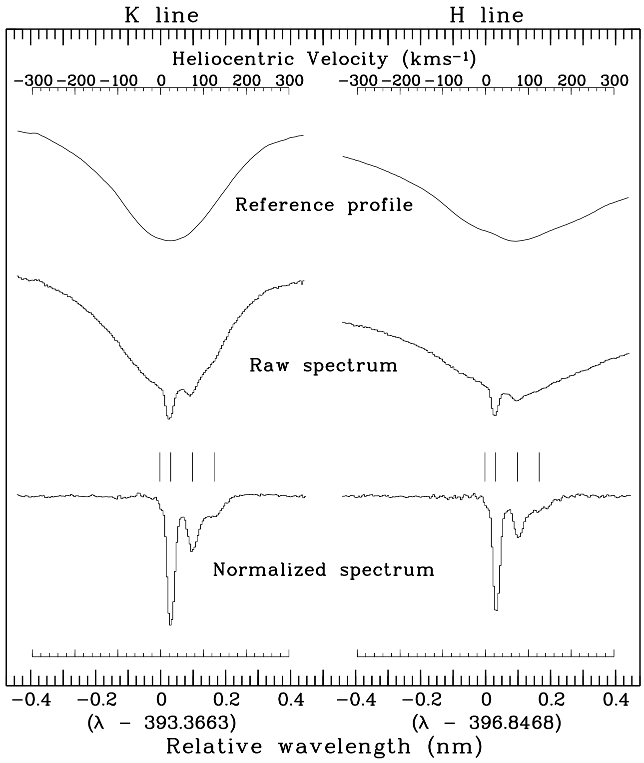

Figure 2: Sample reduced and normalized spectra of β Pictoris obtained on 1998 November 27. The reference profiles used for the normalization are also shown. The normalized spectra have been fitted by four Gaussians whose central velocities are indicated by vertical bars. One corresponds to the deep 'stable' central feature at the stellar radial velocity of $\sim$20 km s^{-1}. One weak blueshifted and two stronger redshifted features have also been fitted. Had the multiple Gaussian fits been plotted, discrepancies between them and the normalized profiles would have been too small to see at the scale of this diagram.

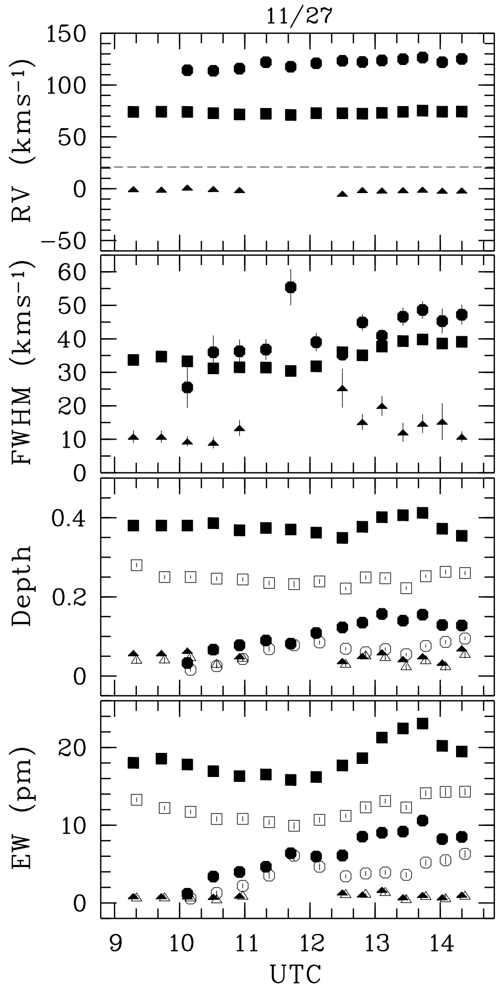

Figure 3: Parameters of the multiple Gaussian fits to the variable absorption features observed on 1998 November 27. The abscissa indicates the time at which different spectra were acquired. The horizontal dashed line represents the radial velocity of the star at which the deep, stable absorption feature occurs (not plotted). Variable absorption features were found to occur at three distinct radial velocities during this night, each of which has been plotted with a different identifying symbol (circle, square, triangle). A given feature is then plotted with the same symbol in all panels of the plot. The velocity and width of each fitted feature were constrained to be the same for the H and K lines, but depths and equivalent widths were fitted independently. They are plotted by open and filled symbols for the H and K lines respectively, and are slightly offset from each other laterally to reduce visual confusion.

2.2 Results

A sample spectrum pair from 1998 November 27 is shown in Fig. 2. The deep, sharp central feature is always present and may be due to decelleration of Ca^+ ions by a ring of H I surrounding β Pictoris (Lagrange et al. 1998), in which case it may exhibit variability on the time scale of years.

Fig. 3 shows the parameters of the individual variable features for the whole of that night. We have acquired a wealth of similar observational material. Some aspects of the entire data set are the presence of absorption activity on almost every night (in our 407 pairs of spectra we detect some 940 variable features—i.e. excluding the central absorption), the clear detection of blue-shifted absorption features, and the emergence of correlations between absorption velocities and absorption widths and depths. In addition, comparison of H & K line depths confirm that higher-velocity features obscure smaller fractions of the stellar disc. We feel we do not understand the scattered-light properties of our spectrograph sufficiently well to make any unequivocal statement concerning the stability or otherwise of the deep central absorption feature. Most interestingly, the H & K equivalent widths of the $\sim$120 km s^{-1} feature on 1998 November 27 evolve jointly in a way evocative of the predictions of Beust & Lissauer (1994) for an FEB in a prograde equatorial orbit. Our observations are compared with one of their models in Figure 1: it must be emphasized that the strength and timescale of the predicted variation depend on assumed properties of the FEB and all that we are claiming is that there is a similarlity of *form* between model and observations. Though daylight occured at the moment when the H line strength might have been expected to exceed that of K, which would have provided a clear confirmation, this may have been the first detection of an FEB transit. Our data set now merits detailed modelling within the context of the FEB hypothesis.

Acknowledgements

This paper summarizes a presentation made at the Second Joint Meeting of the Royal Astronomical Society of New Zealand and the Astronomical Society of Australia. We thank New Zealand's Marsden Fund for curiosity-driven research for financial support.

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