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β Pictoris and other star spectra, in connection with planet formation

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Abstract. We review here the present knowledge on the gaseous phases of debris disks found around MS and old PMS stars, and make an attempt to connect them with planetary system activity.

1. Introduction

The β Pictoris (A5, 20-100 Myrs) disk belongs to the now identified class of "debris fields" that host second generation, short-lived dust, probably due to destructive processes (collisions, evaporation) among larger, km-sized bodies. For a complete definition of debris disks, see Lagrange, Backman and Artymowicz (2000; hereinafter LBA00); see also Stapelfeldt (this volume) and Schneider (this volume). β Pictoris is moreover surrounded by gas, either stable or variable, which presence is probably linked with the solid material. Other stars, especially old PMS stars are also surrounded by large amounts of gas. Even though the gas is not supposed to be abundant enough to impact the dust dynamics in debris disks, knowing about this phases is of interest as it may give informations on 1) the timescales associated to gas removal, and 2) indirect constraints on the solid bodies dynamics and on the presence of planets, if any, as will be developed throughout this paper.

2. β Pictoris spectra and relation to planet formation

2.1. Observations

We briefly outline here the main observational features on the gas around β Pictoris, as well as recent results obtained. For references prior to 2000, see LBA00 and Vidal-Madjar et al, 1998.

Stable gas: Both molecular and atomic species are present around β Pictoris. CO was detected through UV absorption lines, with a density column of 10^{15} cm^{-2}, a kinetic temperature of about 20K (Roberdge et al, 2000). It is probably located at a few 10 AUs from the star. Recently, large amounts (40-50 M$\oplus$) of cold (100K) H_2 were also reported based on the analysis of ISO 12 and 17 μmspectra (Thi et al, 2000). With reasonable hypotheses on the geometrical

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distribution of this gas, this translates into a density column of 10^{22} cm^{-2}, i.e. well above the 10^{19} cm^{-2} upper limit provided by recent FUSE observations (Lecavelier et al, 2000). If we admit that mm observations measure most of the dust mass, found to be about 0.5 M$\oplus$, then ISO data would imply a gas/dust ratio of 100. The similarity with the ISM value, if confirmed, is not straightforward as 1) the dust is not primordial, and 2) giant planets may be already present in the disk, incorporating thus large amounts of gas.

The most abundant atomic species detected so far is CI with a column density of 10^{16} cm^{-2}. HI content is unknown, but constrained through radio observations and simple modeling to be $\leq 10^{19}$ cm^{-2}. Metallic gas is predominantly singly ionized with column densities of about 10^{12}-10^{14} cm^{-2}, depending on the elements. Metals have moreover solar abundances. Most of the CaII (and probably also FeII) is/are close to the star ($\leq$ 1 AU), in a dense and hot medium. The presence of variable CI (see next section) indicates that at least part of CI is produced close to the star, while some could be located further away. This may be also true for the other neutral species.

Importantly, the most abundant atomic or ionic stable gaseous species observed are short lived : CI because of photo-ionization and other elements such as CaII or FeII because of the strong radiation pressure (hereafter RP) they suffer (β ratio $\geq$ 10). CO is also short lived as it is photodissociated on timescales of hundreds of years. As for the dust, these gaseous species have then to be permanently produced.

Spectroscopic variability: Spectacular variable absorptions, mostly redshifted and with redshifts up to 300 km/s occur in the lines of ions singly or twice ionized, and of some neutrals (CI, SI) lines as well. indicating sporadic infalls of gas clouds towards the star. Both the high velocities and the presence of lines arising from metastable levels indicate that the clouds are close to the star ($\leq$ 1 AU). For a close description of these variations, see LBA00. No departure from solar composition has been detected so far among the observed variable metallic species. Based on more than 10 years of observations, the occurrence of redshifted events is a few 100/yr and blueshifted lines are rarely observed.

A last intriguing feature is the presence of over ionized gas (CIV, A1III) at high velocities, not necessarily correlated with those of singly ionized variable gas. In particular, blueshifted lines are more frequently observed for these elements than for singly ionized ones.

2.2. Models for the circumstellar gas around β Pictoris

FEBs as an explanation of the variable gas: It was proposed in the late eighties that the infalling gas was the result of evaporation of dust freshly released from solid, km sized bodies grazing the star and crossing the line of sight. This "Falling Evaporating Body" (hereafter FEB, see ref. prior to 2000 in LBA00) scenario was tested through simulations of grazing and evaporating comets, focusing on the gas production rates and dynamics. under the effect of gravity, RP. and collisions with the other gaseous species. The main characteristics (line strengths and velocity timescales) of the singly ionized variable lines are reproduced assuming 1-10 km bodies evaporate with rates scaled that of our Solar System (SS) comets (Fig. 1).

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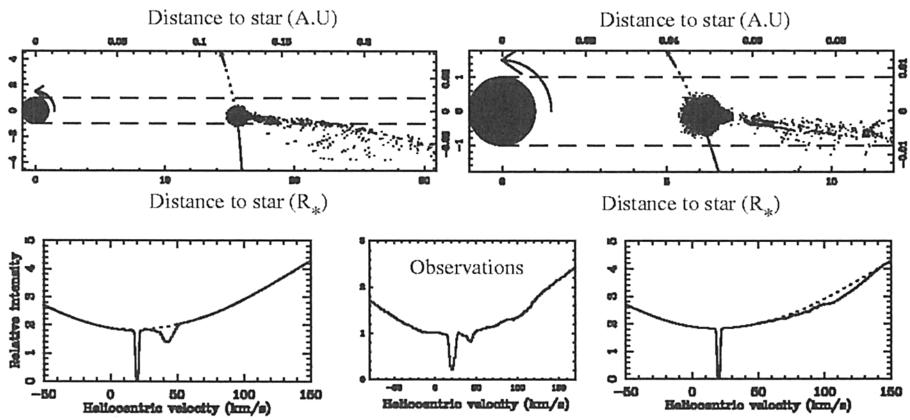

Figure 1. Observed (middle) and simulated (left and right) CaII lines towards β Pictoris , assuming evaporation of 50% (in mass) icy bodies. Both high and low velocity redshifted components are reproduced by the simulation.

If the FEBs originate from typical distances of a few AUs from the star (see below), they are not likely to retain ice on a 10 Myrs timescale (Karmann et al, private communication), i.e. smaller than the age of the system. Assuming non icy FEBs does not actually severely change the results on metallic lines.

Temperature conditions at the shock surface between evaporated gas and surrounding medium may be high enough to produce overionized species (Beust & Tagger, 1993). Modeling has still to be done to test whether this hypothesis quantitatively explains the observed lines.

FEBs as an explanation of the stable lines: Once produced, the gaseous species that suffer strong RP are rapidly expelled and cannot produce any detectable absorption unless they meet some intervening gaseous medium that they might efficiently interact with. A ring of gas insensitive to RP, such as HI or OI, at distances ≥ 0.5 AU, i.e. further than the evaporation region, can trap the ejected gas for a while (typically a few years) in the ring, producing thus quasi stable absorption lines of metallic species close to those observed. CO, which is located further away, requires however another origin. A possible one is comet evaporation at a few 10 AUs (Lecavelier et al, 1997; Roberdge et al, 2000) from the star.

Planet perturbation as an explanation to FEBs: In the scheme of the FEB scenario, a few hundreds of km sized bodies graze (≤ 0.3 AU) the star each year. According to Beust and Morbidelli (2000), random collisions among collisions are not efficient enough to account for the observed infall rate, and planetary perturbations via mean motion resonances (especially 3:1 and 4:1) are to be preferred. In that case, the rate of observable events depends on 1) the resonance width, the time for the bodies to become FEBs (and hence on the planet mass and orbital parameters) and 2) the number of bodies within the resonance and

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the system inclination (edge-on for β Pictoris). The presently available statistics can be accounted for with a Jovian mass planet located on a moderately (0.05-0.1) eccentric orbit of semi major axis of $\simeq$ 10 AUs, and with a longitude of periastron relative to the line of sight of -70°. Interestingly, the required planet mass and distance to star are compatible with the ones deduced from the modeling of the warp seen in scattered light images (Mouillet et al, 1997).

The 4:1 and 3:1 resonances get empty on timescales $\leq$ 1 Myr, i.e. much shorter than the system age. Collisions can help in refilling them. In that case, it is estimated that about 10^{7-8} bodies/AU need to be present outside the resonance to ensure the refill over a timescale $\geq$ 10 Myrs (Beust and Morbidelli, 2000; Thebault and Beust, 2001). In such a case, the total mass evaporated over 100 Myrs is a few M$\oplus$. Alternatively, planet migration, under gas drag (viscous interaction) or interaction with planetesimals could shift the resonances themselves (Quillex and Holman, 2000). The latter show that a planet with an eccentricity of 0.3, and a rate of migration of 1 AU in 1 Myr in a disk of planetesimals allow to produce FEBs. If so, the FEB phases would be very rapid and transient, and indicative of on-going planet migration. The number of bodies necessary to account for the infalling rate has still to be estimated.

3. Others stars spectra and relation to planet formation

3.1. Gaseous content

Spectroscopic CaII or FeII surveys among MS stars revealed possible β Pictoris-like candidates, among which were HR10, HR6519, HR2174. For more detailed informations about these stars, see LBA00. It is worth noticing that CI. a short-lived species, is present around HR6519, and may indicate on-going comet evaporation (Lecavelier et al, 1997), as does the similarity between the 10 μm spectrum and that of comet Halley (Fajardo-Acosta et al, 1993). Except for β Pictoris and HR6519, none of the MS stars with strong IR excess (Vega, α PsA, η Eri) show evidence for circumstellar (CS) CaII, down to levels of about 10^{11} cm^{-2}. Nor do they show evidence for CO, with still model dependent upper limits of about 10^{14} cm^{-2} for Vega and α PsA (Dent et al, 1995; Liseau, 1999).

CO searches gave interesting results on "old" Herbig stars in the recent years. They were successful for a number of systems. In some cases (e.g. HD163296, AB Aur), Keplerian CO disks were found (Mannings and Sargent. 1997; 2000) up to 300-400 AUs. Greaves et al (2000) observations and modeling of the interesting HR 4796 (8 Myrs) system lead to an H_2 upper limit of 1-7 $M_{\oplus}$ and a CO/H_2 abundance ratio $\leq 3.10^{-5}$, ie significantly smaller than in the ISM. CO lifetime around early-type stars is very short against photodissociation or ISM UV flux, unless shielded; at large distances it may be also frozen onto grains(Vidal-Madjar et al, 1994; Kamp and Bertoldi, 2000). CO is therefore not a good tracer of the amounts of CS gas in the systems. Consequently. any result Ori total gas mass or gas/dust ratio derived from CO measurements and from the assumption of a CO/H_2 ratio of 100 is to be taken with care. H_2 is certainly a much better tracer, but unfortunately. very few measurements are available. Interestingly, ISO data revealed large amounts of H_2 in a few systems such as

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49 Cet (10 Myrs), HD135344 (Thi et al, this meeting). Obviously, many more measurements are necessary.

3.2. Spectroscopic variability

A few MS stars show variability possibly similar to that of β Pictoris (see LBA00). Spectroscopic follow-up are necessary to further test this hypothesis.

Spectacular and complex spectroscopic variations are seen around Herbig stars, mostly in the Balmer lines, HeI, ionized or overionized (e.g. CIV, NV) species, and also in neutrals for later than A-type stars. Models including extended, heated chromospheres of moderate (T$\simeq$20,000 K) temperature as well as hot (10^5 K) clumps embedded in strong (10^{-8} – 10^{-7} M_*/yr) winds seem to reproduce quite well the various line profiles observed in a number of non embedded Herbig stars (see e.g. Böhm and Catala, 1995; Bouret and Catala, 1999, and ref. therein). Magnetic fields could moreover play a dominant role in these systems.

Some of the variable features observed towards a few Herbig stars were tentatively attributed to FEB activity (Grady et al, 2000 and ref. therein; Natta et al, 2000 and ref. therein), based on the presence of enhanced redshifted absorptions in the lines of ionized or neutral elements. In many cases, the statement is however based only upon comparison with "standard spectra" and no information on temporal variability is available. In such cases, the FEB explanation is certainly premature. In a few cases, AB Aur (A0, 2-4 Myrs), UX Ori and BF Ori (a few Myrs), and HD100546 (B9V, $\geq$ 10 Myrs), more data are available and allow further discussions.

Importantly, in addition to variable absorptions, these stars exhibit variable emissions, which make it sometimes impossible (e.g. AB Aur, Fig. 2 in Grady et al, 1999) to distinguish extra absorptions from extra emissions, and also photometric and/or polarimetric activities, to a very high level in UX Ori objects. In the case of UX Ori, the strong photometric variations are interpreted (Grinin et al 1996) by obscuration by dust clouds revolving at about 0.5 AU. NaI absorption lines variability is attributed to 30 km sized thermally disrupted and evaporated star grazing bodies, while HeI variations are attributed to collisionally excited gas produced by interaction between the infalling matter and the inner disk. Alternatively, Sorelli et al (96) suggested that magnetically channelled accretion could also be responsible for the clumpy accretion. Vieira et al (1999) attributed HD100546 spectroscopic variability to a combination of 1) stable accretion in a remote and latitudinally extended envelope, 2) a stable wind, and 3) discrete accretion in a inner accretion disk. Obviously, *if at work in such systems, FEB activity is only part of a complex pattern of activities of various origins, and modeling is mandatory* to really test this FEB activity.

4. FEB occurrence and detectability

Our stars of interest, aged more than a few Myrs are good candidates to host FEB activity, as planetesimals and also giant planets may be present. However, it has still to be tested whether or not this activity is *detectable*. This depends on various factors: the star properties, and activity (wind, accretion) and the

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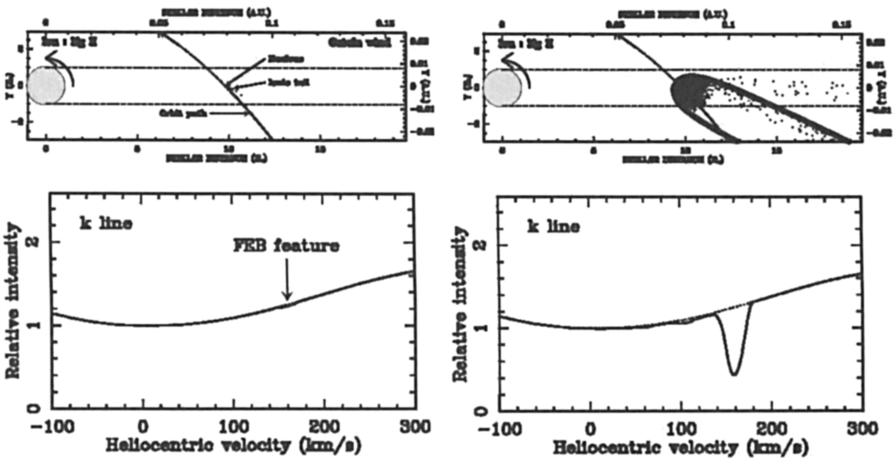

Figure 2. Simulations of FEB signatures around AO type stars with 10^{-8} M_*/yr (left) and 10^{-11} M_*/yr (right) winds. Evaporation rates are scaled from that of SS comets taking into account the star ST.

geometry of the system. We address below the impact of these parameters. The framework for simulation of FEBs is that detailed in Sect. 2.

4.1. Stellar properties

RP prevents the gas from extending radially from the FEB once evaporated. RP from B or early A type stars is high, but simulations (Beust et al, 2000) show that variable lines can still be detectable.

The winds observed arising from Herbig stars act similarly. Depending on the associated mass loss, they can prevent the gas cloud from expanding and hence forming detectable variable lines as seen in Figure 2 (see Beust et al, 2000, for more details). Strong (10^{-8} M_*/yr, ie similar to that proposed for AB Aur; Bouret & Catala, 1999) winds prevent from detecting km-sized FEBs in the present modeling which scales evaporation rates from that of SS comets. Asymmetrical winds, much fainter in the line of sight would help. Wind geometry is poorly constrained so far and theoretical work, combined with observations is certainly required to further progress. Accretion is also a process that will alter the dynamics of the gas and impact on the clouds geometry. Its effect remains to be modeled.

4.2. System inclination

Obviously, edge-on orientation is very favorable to detect FEBs. Assuming planet perturbation in a system inclined by 40°from edge-on (i.e. lower limit for HD100546), events may still be detected. but with a rate 10 times smaller than for an edge-on disk (see Fig. 3).

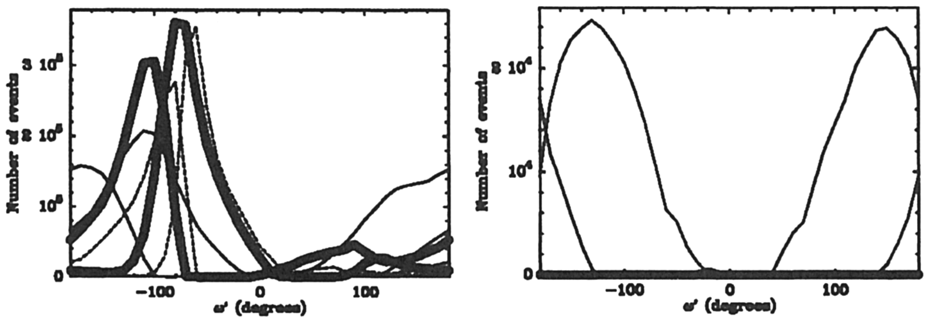

Figure 3. Statistics of FEB events as a function of longitude of periastron of the perturbing planet, in two cases: 0°disk inclination (left) and 40°disk inclination (right). Grey (resp. black) lines correspond to redshifted (resp. blueshifted) events.

4.3. Note : criteria for FEB detection

It was early assumed that the best criterium to find FEB candidate stars was the presence of *redshifted* lines. Figure 3 shows that for a given longitude of planet periastron, FEBs produce either redshifted or blueshifted features. However, for a given system, one "side" predominates. New searches for FEB candidates should take this remark into account.

5. Summary of current understanding and future prospects

β Pictoris itself is an ideal laboratory to develop sophisticated models, both on its dusty and gaseous components. Even though many studies are still needed, it seems that the gaseous phases is linked with the presence of solid km sized bodies and probably also at least one giant planet in the system. Other MS and PMS Herbig stars of ages $\geq$ 10 Myrs are also surrounded by dust and/or gas. The total amounts of gas (and hence the gas/dust mass ratio) are however not well constrained.

In systems aged 10-100 Myrs, one should expect evaporation of star grazing solid bodies to occur. The FEB detectability strongly depends on the star activity, and especially the presence of winds and to a lower extent, on the system orientation as well. FEBs candidates proposed sofar still need to be confirmed. Spectroscopic but also photometric (Lecavelier, 1999) searches for FEB signatures should intensify, in parallel with detailed modeling, taking into account the complex activity at work in the Herbig systems. Also, global modeling, including 3D modeling of the wind and accretion is crucial to further progress. Such efforts are worthwhile as they will allow to characterize large bodies densities and dynamics in outer young planetary systems.

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