Exocomet Circumstellar Fe I Absorption in the Beta Pictoris Gas Disk

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Abstract

We present an archival study of 27 circumstellar Fe I (λ3860 Å) and Ca II (λ3933 Å) absorption spectra of the β Pictoris system recorded over the 2003–2014 timeframe. We have detected several transient absorption events at velocities red-shifted by >+20 km s⁻¹ from the main central absorption line profiles of both Fe I and Ca II. Such events can be attributed to the presence of kilometer-sized infalling evaporating bodies (i.e., exocomets) on their grazing approach to the central star. The majority of the transient absorption events detected in the Fe I profiles occur at velocities in the +35 to +50 km s⁻¹ range. This is consistent with that found for Ca II gas that has been sublimated from the “D” family of β Pictoris exocomets recently found by Kiefer et al. These spectra also reveal that the strength of the main component of the Fe I absorption line at Vhelio ~ +21 km s⁻¹ has weakened by ~30% since 2011. Since neutrals, when ionized, are the main source of the ion-braking mechanism of Brandeker for circumstellar gas in the β Pictoris system, then this may have some measurable effect on the size and/or location of the main circumstellar gas disk. Finally we note that we have failed to detect any circumstellar Fe I absorption in our previously reported spectra of similar gas disks surrounding 28 young A-type stars. Thus, it would appear that the β Pictoris is anomalous with regards to circumstellar Fe I absorption.

Key words: circumstellar matter

1. Introduction

The presence of planetesimals (i.e., exocomets) in the circumstellar gas disk of the young A-type star β Pictoris was revealed by the night-to-night variability of the absorption profile of the Ca II K-line (3933 Å), caused by the evaporation of gaseous products liberated from kilometer-sized icy bodies on their infall toward the central star (Hobbs et al. 1985; Ferlet et al. 1987). During the following 30 years over a dozen more A-type stars with surrounding debris disks of ages <100 Myr have been shown to exhibit similar circumstellar Ca II K-line absorption variability on timescales of hours to a few days (Montgomery & Welsh 2012; Kiefer et al. 2014; Welsh & Montgomery 2015). The study of these star-grazing exocomets allows us the opportunity to investigate the elemental composition of the potential building blocks of planet formation. However, only circumstellar absorption in the Na I D-line and Ca II K and H-lines has been routinely studied at visible wavelengths in these debris disks (Vidal-Madjar et al. 1986; Welsh et al. 1998; Redfield 2007). Although high resolution ultraviolet absorption spectroscopy allows a far wider range of atomic species (such as Al, Si, C, N and O) to be studied in these disk systems, thus far only β Pictoris and 49 Ceti have been studied in any detail at these short wavelengths (Roberge et al. 2000, 2014). For the case of β Pictoris most of the liberated exocomet gas has near-solar composition, whereas carbon is significantly over-abundant relative to both the Sun and to minor bodies in our solar system.

The spatial structure of the extended optical emission from the β Pictoris debris disk gas has been studied by Brandeker et al. (2004) and Nilsson et al. (2012), who have detected over 80 emission lines, with the brightest being those of Fe I, Na I, Ti and Ca II. These data have been incorporated into braking gas models by Brandeker (2011) and Fernandez et al. (2006) to explain the continued presence of metallic gas in the disk at fixed circumstellar velocities. The models work best if the gas disk has an enhanced carbon abundance, which has been shown to be the case for β Pictoris (Roberge et al. 2006). The β Pictoris disk spectra show unusually strong Fe Iλ3859.9 Å line emission. This spectral line, which normally arises in cold (T < 500 K) and neutral gas, is very rarely seen along interstellar sight-lines, and thus its presence in the circumstellar gas disk of β Pictoris is intriguing. The detection of this (weak) line in an absorption spectrum of β Pictoris was first mentioned by Lagrange et al. (1995), and a recent study of 489 absorption spectra of β Pictoris recorded between 2003 and 2008 of (Brandeker 2011) has revealed a small (1 km s⁻¹) radial velocity shift between the central Fe I and Na I absorption components, as predicted by current gas braking models. These
findings led us to search the European Southern Observatory (ESO) data archive for further observations of the (neutral) Fe I line in absorption to examine its behavior with respect to the Ca II K-line, which is a tracer of warmer and more ionized gas in the circumstellar disk. We note that the circumstellar Na I D-line doublet (5890 Å) could also be used to carry out a similar comparison with Ca II, but such (weak) line profiles are usually contaminated by telluric water vapor lines, whereas the Fe I line at 3860 Å is free from such effects.

2. Data Analysis

We have downloaded 27 flux calibrated spectra of the A6V star β Pictoris residing in the ESO Data Archive that were recorded with the HARPS spectrograph ($R \sim 115,000$) installed on the La Silla 3.6 m telescope. Our selection of spectra from the 1000+ that reside in the data archive was based on three criteria. (i) The spectra had a signal-to-noise ratio at 3930 Å of >250:1 in the local stellar continuum, which allowed measurement of a minimum equivalent width (EW) of 1.0 mÅ for the Fe I line at 3860 Å (ii) The dates of spectral observation covered the 2003–2014 time frame in a fairly even manner. We note that the majority of observations residing in the data archive were recorded many times per night in groups of ~2 week periods carried out two or three times per year. (iii) Five of these spectra were selected to cover the 48 hr period from 2013 August 20–22, such that the evolution of any high velocity (HV) transient absorption features could be traced. The downloaded data presented here are in the form of flux and wavelength calibrated spectra, all pre-processed using the HARPS standard data reduction pipeline. We note that all velocities quoted in this paper are in the heliocentric frame of reference.

The focus of our present study is a comparison between the simultaneously recorded Ca II K-line (3933 Å) and Fe I (3859.9 Å) absorption profiles observed over an 11 year period. The main circumstellar absorption component of the Ca II K-line has been shown through numerous observations to be unvaryingly stable at the stellar radial velocity of $V_{\text{helio}} \sim +21$ km s$^{-1}$ (Kiefer et al. 2014) with the disk gas being located at a distance of $\approx 1.5$ au from the central star. This main (disk) absorption component is often accompanied by transient HV (red-shifted) absorption features (often termed “falling evaporating bodies” or FEBs) that are thought to be produced by the vaporization of gas from star-grazing exocometas as they transit in front of the stellar disk on highly eccentric orbits (Ferlet et al. 1987; Beust et al. 1990).

Residual intensity profiles for both the Ca II and Fe I lines (see the examples shown in Figures 1–3) were determined by fitting the local stellar continua with 6th (or higher) polynomials over the velocity range of $\pm 150$ km s$^{-1}$ from the central absorption. Details of the continuum fit process and the measurement of the absorption EWs can be found elsewhere (Welsh & Montgomery 2015). In Table 1 we list the date and (UT) time of each spectral observation together with the (EW$_{\text{FEB}}$) of any HV absorption component in the Ca II K-line profile presumable caused by an FEB event and the velocity range over which the EW of this absorption feature was measured. In addition we list the EW of the main Fe I absorption line originating in the circumstellar gas disk (EW$_{\text{DISK}}$) and, when detected, the (EW$_{\text{FEB}}$) and velocity range of any HV absorption feature detected in the Fe I profile. The velocity of the main Fe I disk absorption line was (within the measurement error) the same as that of the main Ca II-K component (i.e., $V_{\text{helio}} = +21$ km s$^{-1}$).

3. Discussion

The absorption behavior of the circumstellar Fe I 3860 Å absorption line with respect to that of the circumstellar Ca II K-line recorded over the 2003–2014 time-frame is shown in the residual intensity profiles of Figures 1–3, with the corresponding measurements of EW and ranges of absorption velocity listed in Table 1. We do not show all of the 27 Ca II and Fe I absorption profiles in these figures, but instead we have limited our selection to spectral observations that show typical examples of HV Fe I and Ca II absorption components. In addition, we also show Fe I and Ca II spectra that cover the 48 hr period from 2013 August 20–22 such that the evolution of a transient absorption event can be traced. We also note that three of these spectra (marked by asterisks in Table 1) have been presented previously (Welsh & Montgomery 2015). From all of these spectral data we note the following characteristics of circumstellar absorption:

1. The most notable feature in the Fe I spectra is the occasional presence of broad, weak absorption features at velocities red-shifted from the central absorption, which is centered at $V_{\text{helio}} \sim +21$ km s$^{-1}$. Similar transient features have been routinely observed in the circumstellar Ca II K-line spectra of β Pictoris, with their origin being associated with the vaporization of swarms of “FEBs” i.e., exocometas (Beust et al. 1990). Most of the time (9 times out of 11), when HV absorption events were detected in the Fe I line, they were mirrored by absorption events in the Ca II line at similar velocities. In Figure 4 we show the velocity extent of FEB absorption events in the Ca II and Fe I lines for the eleven occasions when they occurred simultaneously. As can be seen by inspection of Figure 4 or Table 1, in all but two occasions, the Fe I and Ca II absorption events occurred over similar ranges of velocity (i.e., $\approx +35$ to $+50$ km s$^{-1}$), suggesting that all of these evaporative events most probably occurred at similar distances ($R < 10 R_\star$) from the star (Beust et al. 1998). Three examples of these simultaneous Fe I and Ca II absorption events are shown in Figure 1.

The velocity range over which these nine absorption events took place in the Fe I and Ca II profiles (i.e., $\approx +35$ to
+50 km s\(^{-1}\)) is similar to the narrow velocity range recently attributed to the evaporation of exocomets belonging to the so-called “D” family (Kiefer et al. 2014). Their comprehensive study of >1000 Ca\(\text{II}\) K-line absorption events revealed the presence of two families of exocomets in the β Pictoris system. The “D” exocomet family was preferentially observed in Ca\(\text{II}\) absorption data over a narrow range of velocities \((V_{\text{helio}} = +36 \pm 6\) km s\(^{-1}\)), implying that they originate from the same orbital direction and share the similar orbits. On the other hand, the “S” family of exocomets seen toward β Pictoris was associated with a much wider range of absorption velocities \((V_{\text{helio}} = +57 \pm 55\) km s\(^{-1}\)), implying that they come from a wider range of directions.

On two occasions, however, the absorption events that were detected simultaneously in both the Fe\(\text{I}\) and Ca\(\text{II}\) lines did not share the same absorption velocity range. While Ca\(\text{II}\) FEB

**Figure 1.** Residual intensity absorption spectra of the circumstellar Ca\(\text{II}\)-K (3933 Å) and Fe\(\text{I}\) (3860 Å) lines observed toward β Pictoris on the dates listed on each plot. Equivalent widths (EW) of various absorption components (as listed in Table 1) are indicated by arrows. The appreciable HV absorption features seen in the Ca\(\text{II}\) spectra are also (weakly) detected over a similar velocity absorption range in the Fe\(\text{I}\) profiles.
Figure 2. Residual intensity absorption spectra of the circumstellar CaII-K (3933 Å) and FeI (3860 Å) lines observed toward β Pictoris on the dates listed on each plot. Equivalent widths (EW) of various absorption components (as listed in Table 1) are indicated by arrows. The appreciable HV CaII absorptions at $V \sim +75$ km s$^{-1}$ and $V \sim +55$ km s$^{-1}$ (respectively detected in the 2007 and 2008 spectra) have no absorption counterparts in the corresponding FeI profiles. Conversely, the HV absorption at $V \sim +60$ km s$^{-1}$ seen in the 2009 FeI spectrum has no absorption counterpart in the corresponding CaII profile.
Figure 3. Residual intensity absorption spectra of the circumstellar Ca II-K (3933 Å) and Fe I (3860 Å) lines observed toward β Pictoris that show the evolution of a high velocity Fe I FEB event at $V \sim \pm 50$ km s$^{-1}$ over a 48 hr period from 2013 August 20–22.
events took place within the velocity range associated with the “D” family of exocomets (i.e., +25 to +50 km s\(^{-1}\)), the Fe\(_1\) absorption events took place at higher velocities of +50 to +75 km s\(^{-1}\) (see Figure 4). On many occasions (16 times out of 27), HV Ca\(\pi\) FEB absorption was detected without any Fe\(_1\) counterpart. In Figure 2 we show two examples of HV Ca\(\pi\) absorptions with velocities >60 km s\(^{-1}\) that have no HV FEB absorption counterpart in the Fe\(_1\) spectra (see the 2007 and 2008 data).

Of the eleven spectra showing a HV Fe\(_1\) absorption event, only three occurred at velocities >+45 km s\(^{-1}\). Such velocities are well outside the narrow range of velocities attributed to the “D” family of exocomets, but well within the velocity range associated with the “S” exocolon family (Kiefer et al. 2014). In two of these three cases (2010 November 19 and 2013 August 21), the HV Fe\(_1\) absorption was accompanied by Ca\(\pi\) absorption at similar high velocities. However, this was not the case for the 2009 spectrum shown in Figure 2 that shows no Ca\(\pi\) absorption counterpart to the Fe\(_1\) HV absorption at \(V_{\text{helio}} \sim +65\) km s\(^{-1}\).

We note that this is the first time that multiple transient FEB absorption events have been reported for the circumstellar Fe\(_1\) line observed toward \(\beta\) Pictoris. Furthermore, we have retroactively searched all of our recent high resolution spectra recorded toward 28 other circumstellar disk systems associated with young (<400 Myr) and fast rotating A-type stars (Montgomery & Welsh 2012; Welsh & Montgomery 2013, 2015), but have failed to find any measurable absorption associated with the main component of the Fe\(_1\) line at 3860 Å. Thus, with respect to Fe\(_1\) absorption, the \(\beta\) Pictoris circumstellar disk gas seems anomalous.

(2) We have seen from Figure 4 that in many cases the velocity range of FEB absorption is similar for both the Fe\(_1\) and Ca\(\pi\) lines. In Figure 5 we plot the EW of the Fe\(_1\) FEB absorption events versus the EW of the Ca\(\pi\) FEB events. We only plot data from the nine cases in which the velocity ranges of Fe\(_1\) and Ca\(\pi\) FEB absorption are similar (i.e., we omit the 2009 February 16 UT02:18:50 and 2013 August 21 data points). We see that when the Ca\(\pi\) FEB absorption is weak
(i.e., EW < 120 mÅ) there is an approximate linear relationship with the Fe I FEB EW. However, the four points on the graph located at a Ca II FEB EW of 150 mÅ do not follow this trend. This is mainly because these nearly saturated Ca II FEB absorption profiles most probably consist of more than one absorption component (as shown in the 2013 data of Figure 3). In Table 1 we have reported the total EW of these strong Ca II FEB absorption events, of which only a fraction of the listed EW value is probably physically associated with the corresponding Fe I FEB absorption event.

(3) The evolution of the circumstellar absorption profiles of both Ca II and Fe I has been tracked over the 48 hr period from 2013 August 20–22, as shown by the spectral profiles shown in Figure 3. An HV feature of EW ~ 150 mÅ spanning the +35 to +57 km s⁻¹ velocity range is prominent in the Ca II-K profiles for 3 spectra recorded on 2013 August 20, but this absorption reduces to an EW ~ 60 mÅ over the following 48 hr. A weak Fe I HV absorption feature spanning the +30 to +50 km s⁻¹ velocity range is observed in the latter two spectra recorded on 2013 August 20 and, in a similar manner to that exhibited in the Ca II spectra, this absorption reduces to a level below our detection threshold over the following 48 hr. This behavior would imply that since the HV Fe I and Ca II FEB absorptions are observed with similar velocities, then these evaporative events are most probably formed within a similar circumstellar location ≤10R∗ (Beust et al. 1998).

In addition to this HV absorption feature the three Ca II profiles recorded on 2013 August 20 also show an additional HV absorption component spanning the +80 to +110 km s⁻¹ velocity range. This feature has an EW ~ 70 mÅ which reduces to an EW ~ 20 mÅ over the following 48 hr. There is no corresponding Fe I (FEB) absorption component detectable within this velocity range in the three spectra recorded on 2013 August 20, or in the spectra recorded over the following 48 hr (see Figure 3). The velocity range of this HV Ca II absorption is consistent with that found for the “S” family of exocomets which are thought to be distributed over a broad range of velocities Vhelio = 57 ± 55 km s⁻¹ (Kiefer et al. 2014). Such comets probably come toward the central star from a wide range of directions, and have relatively broad and shallow Ca II absorptions. They are hypothesized to transit at shorter distance from the star (~10 stellar radii) and to be relatively depleted of volatiles from their many approaches toward β Pictoris. Their characteristics are consistent with an old population of comets trapped in a mean motion resonance with a massive planet. Since we do not observe any significant Fe I absorption with velocities >+70 km s⁻¹ it would appear that either this type of exocomet swarm may have a low level of Fe metallicity (consistent with them being of an old age) or these infalling bodies evaporate much closer to the central star and as such the liberated gas is more easily ionized (ionization potential of Fe I = 7.9 eV) and is thus detectable as Fe II at UV wavelengths.

(4) Using high resolution spectra recorded in 1991, Lagrange et al. (1995) first reported an EW of ~9.0 ± 1 mÅ for the weak circumstellar Fe I line detected toward β Pictoris. Measurements of the present archival spectra reveal that the strength of the main Fe I absorption line (centered at Vhelio = +21 km s⁻¹) seems to have weakened from an average EW = 6.3 ± 0.5 mÅ (i.e., a column density of N(Fe I) ~ 2.5 × 10¹² cm⁻²) measured
over the 2003 to 2011 timeframe to an average $\text{EW} = 4.1 \pm 0.4 \text{ mA}$ (i.e., $\text{N(Fe I)} \sim 1.6 \times 10^{12} \text{ cm}^{-2}$) measured from 2013 onwards. In order to confirm this apparent weakening of absorption by the Fe I circumstellar disk gas we have accessed an archival spectrum of $\beta$ Pictoris recorded on 2014 February 07 (UT01:02:25) with the FEROS coude echelle spectrograph ($R \sim 48,000$) mounted on the ESO 2.2 m telescope. An $\text{EW} = 4.7 \pm 0.5 \text{ mA}$ was derived for the main Fe I absorption profile, consistent with the weakening of the Fe I line observed in the higher resolution HARPS spectra.

We can conjecture two possible scenarios that could account for the apparent weakening of the Fe I gas absorption. First, if the (stable) circumstellar disk is not being as regularly replenished with neutral Fe I gas from the vaporization of exocomets, or the family of exocomets themselves contain less Fe, this could account for the diminished Fe I gas absorption. Second, if the (stellar) ionization of the vaporized gas has increased slightly then we might expect to observe more circumstellar Fe II and less Fe I. We note that no weakening of the central component of the circumstellar Ca II K-line absorption profiles has been observed over the same timeframe. When ionized, neutrals such as H I, Na I, C I, N I and Fe I, are the dominant sources of the ion-braking mechanism forward by Brandeker (2011) for the $\beta$ Pictoris system. Thus, it would be useful to know if this apparent reduction in Fe I replenishment has had any measurable effect on the size or location of gas in the the “stable” circumstellar disk surrounding $\beta$ Pictoris. If the disk is now closer to the central star, then this could account for an increase in the ionization of the circumstellar gas.

(5) The two Fe I spectra recorded on 2009 February 16 are particularly interesting since the spectrum taken at UT 02:18:50 shows appreciable HV absorption (EW $\sim 5 \text{ mA}$) spanning the $+45$ to $+66 \text{ km s}^{-1}$ velocity range with no corresponding Ca II-K absorption in the same velocity range. The data recorded 70 minutes later at UT 03:28:20 shows no sign of the HV Fe I absorption. We have checked that the Fe I HV feature at $V \sim 55 \text{ km s}^{-1}$ is real since it also appears at similar velocities in the Fe I spectra recorded up to one hour earlier than UT 02:18:50. This illustrates the highly transient nature of FEB events, in that evaporated exocomet gas can have very short observable lifetimes over certain velocity ranges.

4. Conclusions

Our archival study of circumstellar absorption observed toward $\beta$ Pictoris over the 2003 to 2014 timeframe has revealed transient absorption events at velocities red-shifted by $>20 \text{ km s}^{-1}$ from the main central absorption line profiles of both Fe I (3860 Å) and Ca II (3933 Å). Such events can be attributed to the presence of kilometer-sized infalling evaporating bodies (FEBs) on their grazing approach to the central star. The Fe I FEB absorption events, when detected, are usually observed at the same redshifted velocity as the Ca II FEB absorption events (i.e., $+35$ to $+50 \text{ km s}^{-1}$). This is consistent with that found for Ca II gas that has been sublimated from the “D” family of $\beta$ Pictoris exocomets (Kiefer et al. 2014). For such Ca II FEB events with EWs $< 120 \text{ mA}$ the corresponding Fe I FEB EWs are $\sim 30$ times weaker.

These spectra also reveal that the strength of the main circumstellar component of the Fe I absorption line at $V_{\text{helio}} \sim +21 \text{ km s}^{-1}$ has weakened by $\sim 30\%$ since 2011. Since neutrals, when ionized, are the main source of the ion-braking mechanism proposed by Brandeker (2011) for circumstellar gas in the $\beta$ Pictoris system, then this may have some measurable effect on the size and/or location of the main circumstellar gas disk.

We note that nearly all of our detections of Fe I FEB absorption occurred within a narrow range of velocities ($+35$ to $+50 \text{ km s}^{-1}$) that may be associated with the “D” family of exocomets, with only a few detections of Fe I FEB events with velocities in the $+45$ to $+65 \text{ km s}^{-1}$ range. No Fe I FEB events have been detected with absorption velocities $>70 \text{ km s}^{-1}$, even when such FEB events were present in the Ca II line profiles.

Clearly there still remain many questions to be answered concerning the composition, location and ionization state of the circumstellar gas disk(s) surrounding $\beta$ Pictoris with respect to its replenishment by the evaporation of exocomets. This can only be accomplished with high resolution absorption spectra recorded at UV wavelengths that enables neutral, partially ionized and fully ionized gas to be sampled simultaneously.

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