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LETTER

Letter to the Editor

Discovery of C I around 51 Ophiuchi*

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Abstract. We present the discovery of cold C I in the 51 Oph environment, with a column density of N=5 $\times$ 10^{13}cm^{-2} and temperature $T \approx$ 20K. This is the first β Pic-like star other than β Pic with simultaneous detection of cold dust and gas. The C I/infrared continuum ratio and consequently the gas/dust ratio are similar to the β Pic ones. Since C I has a very short lifetime, it must be continuously replenished, probably by molecular gas dissociation. This provides evidence for the presence of evaporating bodies. A new upper limit on CO content is also given.

Key words: stars: 51 Oph – circumstellar matter – planetary systems – line: profiles

1. Introduction

The IRAS satellite has shown that infrared excesses are a quite common feature around nearby stars (Aumann et al. 1984). These excesses have been interpreted as due to the presence of dust debris disks and have been subject to detailed analyses (see the review by Backman & Paresce 1993). Only the β Pic disk has been imaged with different techniques (Smith & Terrile 1984, Lecavelier des Etangs et al. 1993, Golimowski et al. 1993, Kalas & Jewitt 1995). Also only in that case, the gaseous counterpart has been unambiguously identified. In this Letter, we present new GHRS-HST spectra of the 51 Oph environment with the discovery of C I absorption. We show that this cold gas is probably connected to the presence of Far Infrared (FIR) excess due to dust thermal emission. It is thus only the first case other than β Pic where the gas/dust ratio is estimated and this brings new clues that material is supplied by evaporating bodies.

Because 51 Oph is a B9.5e star (= HR 6519, m_v=4.8, d=70 pc, $v \sin i$=220 km s^{-1}, age $\sim 3\times10^6$ years), its infrared excess is perhaps less surprising than for main sequence stars. However, its abnormal position in color diagrams first noted by Coté et al. (1987) shows that the infrared emission due to free-free emission is negligible. 51 Oph is the only Be star out of a sample of one hundred shown to have an infrared excess associated with circumstellar dust (Waters et al. 1988). The FIR energy distribution definitively confirms the presence of cold dust, even at large distances ($\gg$100 AU). It has also been demonstrated with infrared spectroscopy that the 10 μm excess shows silicate band emission similar to comets and β Pic (Fajardo-Acosta et al. 1993).

Gaseous absorption lines have already been observed in the visible (Lagrange-Henri et al. 1990), and in the UV with IUE (Grady & Silvis 1993). In particular, IUE observations showed the presence of over-ionized species, as well as accretion and spectroscopic variations very similar to the β Pic ones (for a detailed analysis of β Pic IUE spectra, see Deleuil et al. 1993). All of these components are signatures of warm, collisionally ionized gas and accreting material, probably linked to the Falling-Evaporating-Bodies (FEB) phenomenon observed around β Pic (Beust et al. 1990).

However, the connection between these gaseous absorption lines and the dust thermal emission was still missing. In this letter, we present new GHRS-HST spectra of the 51 Oph environment with the discovery of C I absorption. This is the first result of our HST-GHRS program started to better constrain the

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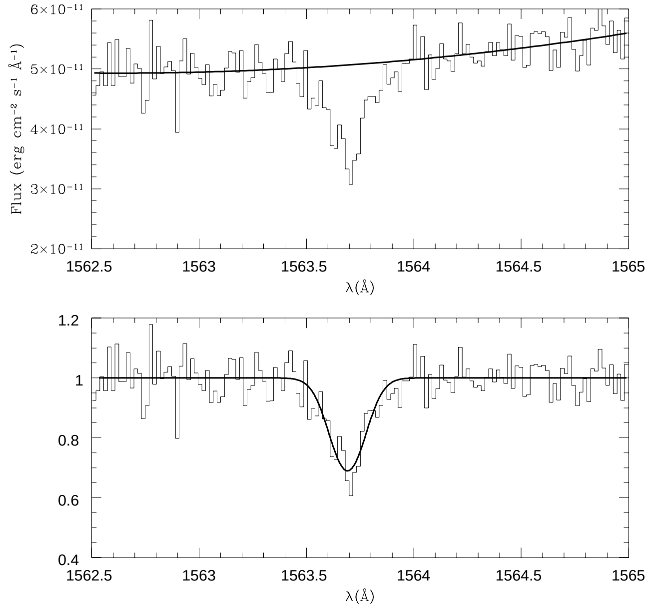

Fig. 1. a) The Fe II line (λ_0=1563.79, E_l=2340 cm^{-1}). The histogram shows the observed spectrum. The solid line gives the continuum fitted by a polynomial with degree determined by a cross-validation method (here degree=2). **b)** Fit of the line by a Voigt profile (N=4.4$\times$10^{13}cm^{-2}, $v_{\rm Dop}$=$-$19$\pm$3km s^{-1}).

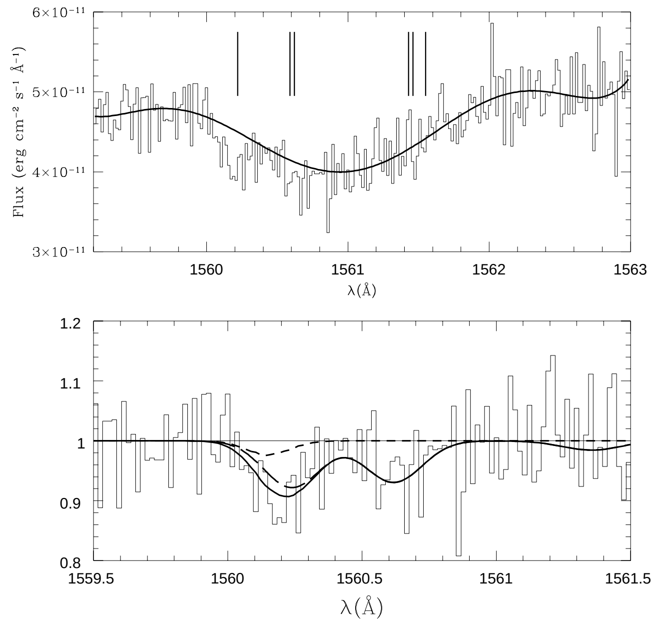

Fig. 2. a) Same as the previous figure for the C I line region. The continuum has been fitted by a 7$^{\rm th}$ degree polynomial. The vertical tick marks show the position of the expected C I lines. **b)** Spectrum obtain after division by continuum. The short-dotted line shows the estimated contribution of the Fe II line (λ_0=1560.251Å, E_l=2340 cm^{-1}). The C I line from ground level is clearly detected (λ_0=1560.309Å). The lines from energy level E_l=16.4 cm^{-1} (λ_0=1560.682Å, λ_0=1560.709Å) are also visible. The lines from energy level E_l=43.4 cm^{-1} are not detected. This strongly constrains the temperature determination. The long-dotted line shows the best fit of the six lines with Voigt profiles and 4 free parameters ($N_{\rm total}$=4.1 $\times$ 10^{13}cm^{-2}, b=26km s^{-1}, $v_{C\,I}$=$-$15$\pm$3km s^{-1}, T= 20 K). The solid line show the best fit to the observations obtained by the addition of the Fe II and C I lines

gas content of four stellar systems with already known circumstellar absorption lines. The detailed analysis of the observations toward the three other stars, which mainly concern the hot central part of the gaseous disks with the detection of very excited species, will be presented in a forthcoming paper (Lecavelier des Etangs et al. 1997). This letter is focused on the new discovery of neutral carbon (C I), mainly at the same radial velocity as the star. The observations and data analysis are presented in Sect 2 and 3. The results and discussion will be found in Sect 4 and 5.

2. Observations

The observations of 51 Oph were executed on 21 Feb. 1996. Observations were done with the oversampling mode, which samples four data points per resolution element, and exposure times necessary to reach a S/N ratio of about 20 per data point. All data were also gathered in the "fp-split" mode, which splits the total exposure time in four sub-exposures at four different positions of the grating in order to decrease the noise from the photocathode granularity. The four different shifts have been estimated by cross-correlation with *IDL* software.

3. Data analysis

The C I multiplet is composed of one line from the ground level (E_l=0, λ_0=1560.3092Å), two lines from an exited level where the energy of the lower level is E_l=16.4 cm^{-1} (E_l=23.6 K, λ_0=1560.6822Å, λ_0=1560.7090Å), and three lines from E_l=43.4 cm^{-1} (E_l=62.4 K, λ_0=1561.3402Å, λ_0=1561.3667Å and λ_0=1561.4384Å) (Morton 1991). The star's radial velocity has been determined from observed strong lines (Fe II metastable levels, Si II, etc...); we find v_*=$-$17 $\pm$ 3km s^{-1} (all velocities are heliocentric). Thus, the first C I absorption line expected to be at zero velocity must be observed at 1560.22$\pm$0.02Å. The presence of an absorption line is clearly visible exactly at that position, and is detected with a very high confidence level. Taking into account 9 pixels around 1560.22Å, we obtain a χ^2_9=20, which gives a detection at confidence level of 98%. However, a metastable Fe II line from energy level E_l=2430 cm^{-1} is also present at λ_0=1560.251Å, and could be responsible for this detection, especially given that the detection of the C I lines from excitation potential E_l=16.4 cm^{-1} is rather faint, and the lines from E_l=43.4 cm^{-1} are not detected (see below).

Fortunately, another Fe II line from E_l=2430 cm^{-1} is also present at λ_0=1563.79Å, and this line is clearly detected. It has an oscillator strength ten times larger than the line at λ_0=1560.251Å. The line at λ_0=1563.79Å has been fitted (N=4.4 $\times$ 10^{13}cm^{-2}, Fig 1), and assuming that the absorber is optically thin, i.e. not small in area and opaque, the corresponding estimate of the expected line at 1560.251Å has been subtracted, although it is very faint and definitely negligible: we conclude that the main part of the absorption feature around 1560.2Å is due to C I absorption. This conclusion is moreover confirmed by the detection of a faint component at 1560.58Å in very good agreement with the expected position of the line from E_l=16.4 cm^{-1} (the line was expected to be found at λ=1560.59±0.02Å).

All of these lines are fitted with Voigt profiles following the procedure defined by Lemoine et al. (1995). The continuum is fitted by a polynomial with degree determined by a cross-validation method. The best fit is then obtained by the search of χ^2 minimum in the parameter space with a simulated annealing.

4. Results

After determining the characteristics of the Fe II line's (Fig 1), and dividing the C I spectrum by the continuum, the expected Fe II line (λ_0=1560.251Å) is subtracted. Finally, the C I multiplet spectrum is fitted by 6 Voigt profiles with 4 free parameters: wavelength shift of the line ($v_{C\,I}$), intrinsic line width (b), total column density (N_{total}) and temperature (T). The first two parameters are assumed to be the same for each profile of the six C I lines. The temperature is given by the relative population of each level assuming a Boltzmann law. Since the second level is less populated than the first one, the ratio strongly constrains the temperature measurement. The third level (E_l=62.4K) is not detected, which is consistent with the ratio of the first two levels.

The best fit is found for $N_{\mathrm{total}}=4.1\times10^{13}\mathrm{cm}^{-2}$, b=26km s^{-1}, T=20K, $v_{C\,I}=-15$km s^{-1} (Fig 2). In detail, for each excitation potential we obtain $N_0=1.2\times10^{13}\mathrm{cm}^{-2}$, $N_{16.4}=1.1\times10^{13}\mathrm{cm}^{-2}$, $N_{43.4}=2.5\times10^{12}\mathrm{cm}^{-2}$.

5. Discussion

The column densities observed in other lines are much smaller than what would be expected if these C I lines were to have an interstellar origin. The C I gas is thus obviously in the circumstellar environment.

Considering 51 Oph's velocity of -17 km s^{-1}, as measured with other lines, we obtain a relative radial velocity of (2±3km s^{-1}) for the C I gas. This zero velocity is in strong contrast to highly redshifted absorption lines observed by Grady & Silvis (1993). This indicates two distinct components: a first component with hot, strongly ionized and high velocity redshifted gas, and a second one with a colder, neutral and large-radius gaseous disk, mainly at the same radial velocity as the star.

These two components are also observed in the β Pic case, which provides a very useful comparison because it is very well studied. In addition to the dust component observed at many wavelength and with many techniques, β Pic is the only main sequence star for which C I and CO have been detected. C I lines towards β Pic give $N_{C\,I}=1.4\times10^{15}\mathrm{cm}^{-2}$, b=7 km s^{-1}, $T\gg60$K, $\Delta v\approx0$ km s^{-1} (Lagrange 1996). CO is also detected at the star's radial velocity with $T\sim30-50K$, $N_{CO}=1.4\times10^{15}\mathrm{cm}^{-2}$ (Vidal-Madjar et al. 1994). As C I and CO are very rapidly destroyed by interstellar UV, they must be continuously resupplied ($\tau\sim1000$ years). The most obvious replenishment mechanism is the evaporation of cometary bodies. Such bodies may be related to the FEBs suggested to explain the sporadic redshifted absorption lines (Beust et al. 1990, Vidal-Madjar et al. 1994) or Orbiting Evaporating Bodies (OEB) suggested to explain the dust component (Lecavelier des Etangs et al. 1996). Importantly, CO and C I have the same lifetime, and CO is dissociated into C I + O I. Then, the same column density gives evidence that the C I is mainly produced by CO dissociation. In addition, the large width of the C I line can be related to the residual energy of the UV dissociating photon transformed into kinetic energy.

CO may be present around 51 Oph as a source of C I. The non-detection of CO lines at 1544Å gives an upper limit $N_{CO}\lesssim5\times10^{14}\mathrm{cm}^{-2}$ (Lecavelier des Etangs 1996). Moreover as the CO lifetime is equal to the C I lifetime, $N_{CO}\leq N_{C\,I}$. The C I detection gives thus a new upper limit of $N_{CO}\leq5\times10^{13}\mathrm{cm}^{-2}$. From a simple geometrical model of a disk with a 10^o opening angle and a characteristic radius of $r\sim100$ AU, we can deduce an upper limit to the total CO mass: $M_{CO}\lesssim10^{19}$kg, which improves the upper limit given by Zuckerman et al. (1995): $M_{CO}\lesssim5\times10^{22}$ kg.

Finally, the low temperature of C I towards 51 Oph is more puzzling. In β Pic, the three C I levels are populated showing that the temperature is larger than the exciting temperature of the third level: this gives $T\gg60$K (Vidal-Madjar et al. 1994). However, recent observations of the C I line towards β Pic at high resolution with Echelle-A show that the C I feature may have at least two components. It is possible that one of these components is cold.

It is interesting to make a rough comparison of the gas/dust ratio in 51 Oph with that in the β Pic system. The gas/dust can be estimated through the C I/infrared continuum ratio under the assumption that the gas and the dust responsible for these spectral features occupy the same volume. This ratio may indicate the status of disk dispersal and evolution of large bodies. For 51 Oph the dominant part of the dust is about 400 K and its emission peaks near 12μm (Fajardo-Acosta et al. 1993). We calculate a total grain emission area of $\sigma_{51\ \mathrm{Oph}}=3.8\times10^{22}\mathrm{m}^2$. For the cooler and less luminous star beta Pic, the main dust population is about 110 K and peaks near 60μm (Backman & Paresce 1993). The corresponding grain emission area is $\sigma_{\beta\ \mathrm{Pic}}=2.1\times10^{23}\mathrm{m}^2$, 5.5 times larger than around 51 Oph. For a population of grains smaller than 10μm the emissivity at 60μm will be approximately 5 times smaller than at 12μm, thus the geometric area of the β Pic grains can be estimated to be roughly 25 times that in the 51 Oph system. The total mass of grains is not sensitive to the exact values of the common grain size in each system so long as they are both smaller than 10μm because the emissivity and mass/area ratio are both proportional to grain size. If we then consider the ratio,

$$\Gamma\equiv N_{C\,I}/M, \quad (1)$$

we get

$$\Gamma_{51\ \mathrm{Oph}} \sim 0.8\ \Gamma_{\beta\ \mathrm{Pic}} \qquad (2)$$

This comparison is only a rough calculation, but shows that the carbon gas content in the two systems is approximately proportional to the dust content despite a factor of 30 difference in $N_{C\ I}$ between the two systems.

From the C I column density, and assuming a disk geometry with a 10^o opening angle and a characteristic radius of $r \sim 100$ AU, the total mass of C I must be about $M_{C\ I} \sim 10^{19}$ kg. The infrared excess gives a mass of cold dust around 51 Oph of about $M_d \gtrsim 10^{22}$ kg. The CO/dust ratio is then $M_{CO}/M_d \sim M_{C\ I}/M_d \lesssim 10^{-3}$. This ratio is very different from the interstellar one. Moreover, if the dust and C I are supplied by evaporating bodies, the $M_{C\ I}/M_d$ ratio is expected to be about 10^{-3}, because the mass production rate must be about the same for dust and carbon, and the dust grains have a lifetime about 10^3 times larger than C I (Lecavelier des Etangs et al. 1996).

6. Conclusion

We have detected the presence of cold C I in the 51 Oph environment. From the short lifetime of neutral carbon, which is quickly ionized, we conclude that it must be continuously resupplied by dissociation of molecular gas. This brings new clues to the presence of evaporating bodies around stars with far infrared excesses. This is only the second case after β Pic of coupled detection of cold gas and dust. The gas/dust ratio is very different from the interstellar ratio while the C I/infrared ratio is similar to the β Pic one. This also favors the evaporating origin of both dust and gas.

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