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Letter to the Editor

The composition of circumstellar gas and dust in 51 Oph*

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Abstract. We analyze ISO archive data of the nearby bright emission-line star 51 Oph, previously classified as a proto-planetary system similar to β Pic. The infrared spectrum reveals the presence of gas-phase emission bands of hot (~850 K) CO, CO_2, H_2O and NO. In addition to this, partially crystalline silicate dust is present. The solid-state bands and the energy distribution are indicative of dust that has formed recently, rather than of debris dust. The presence of hot molecular gas and the composition of the circumstellar dust are highly unusual for a young star and are reminiscent of what is found around evolved (AGB) stars, although we exclude the possibility of 51 Oph belonging to this group. We suggest several explanations for the nature of 51 Oph, including a recent episode of mass loss from a Be star, and the recent destruction of a planet-sized body around a young star.

Key words. circumstellar matter – stars: emission-line – stars: evolution – stars: 51 Oph – infrared: stars

1. Introduction

51 Ophiuchi (HR 6519) is a bright ($V = 4.78$), nearby ($d =$ 131 pc) emission-line star. Although the star has traditionally been classified as B9.5Ve (Buscombe 1963; Slettebak 1982; Jaschek & Jaschek 1992; Dunkin et al. 1997), recent work by Gray & Corbally (1998) show 51 Oph to be of spectral type A0II–IIIe, more in line with its position to the right of the main-sequence in the Hertzsprung-Russell diagram (van den Ancker et al. 1998). For the current generation of ground-based telescopes, 51 Oph is a point-source at visual to mid-infrared wavelengths (Merkle et al. 1990; Lagage & Pantin 1994).

51 Oph exhibits a normal UV and visual energy distribution, but IRAS and subsequent ground-based follow-up observations revealed an unusually large infrared excess longward of 2 μm, interpreted as being due to hot (up to 1000 K) circumstellar dust (Coté & Waters 1987; Waters et al. 1988). The peculiarity of the energy distribution of 51 Oph when compared to those of Be, Ae and A-shell stars led Waters et al. (1988) to suggest that it may be a candidate proto-planetary disk system, similar to β Pictoris. This suggestion was further strengthened by Grady & Silvis (1993), who found evidence for the presence of variable columns of accreting gas, similar to those found around β Pic.

The presence of dust in the 51 Oph system was unambiguously established in 1993, when Fajardo-Acosta et al. detected a prominent 10 μm silicate feature in emission. Their results were subsequently confirmed from the ground by Lynch et al. (1994); Walker & Butner (1995); Sylvester et al. (1996); by Waelkens et al. (1996) using the *Infrared Space Observatory* (ISO; Kessler et al. 1996). Lecavelier des Etangs et al. (1997) found cold neutral C ($N = 5\ 10^{13}$ cm^{-2}, $T = 20$ K) in 51 Oph, yielding a C I/dust ratio similar to that derived for β Pic. Since C I has a very short lifetime, it must be continuously replenished, providing evidence for the existence of evaporating bodies in 51 Oph, similar to those inferred around β Pic.

However, the analogy with the β Pic system is not complete. 51 Oph possesses strong Hα emission, absent in β Pic. The shape of the spectral energy distribution suggests that only very few large dust grains are present, unusual for a protoplanetary disk, but in agreement with what is found in Vega-type systems. However, the magnitude and temperature of the infrared emission is more reminiscent of disks surrounding younger stars. These indicators, together with its position to the right of the main-sequence, lead some authors to consider 51 Oph to be related to the Herbig Ae/Be stars (e.g. van den Ancker et al. 1998; Meeus et al. 2001).

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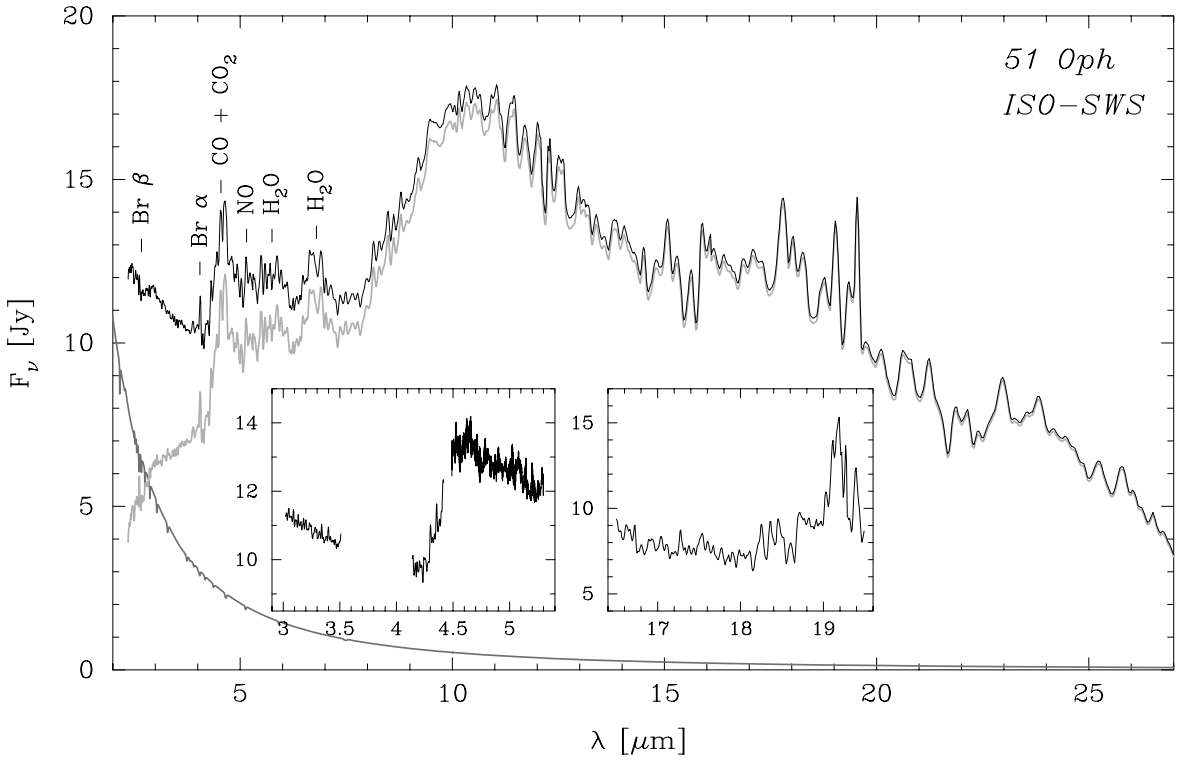

Fig. 1. ISO-SWS spectra of 51 Oph. The main figure shows the AOT 01 spectrum, whereas the insets show the AOT 06 data. The grey lines show a Kurucz (1991) model for the A0 primary (dark) and the spectrum (light) obtained by subtracting this photosphere model from the observed spectrum

In this *letter* we will re-analyze archive ISO spectroscopy of 51 Oph. We will show that its 4–8 μm spectrum, not shown by Waelkens et al. (1996), reveals the presence of hot circumstellar molecular gas. This is highly unexpected for a proto-planetary or debris disk system. We investigate several different explanations for the remarkable composition of the circumstellar material in 51 Oph and comment on those.

2. Observational data

ISO observed 51 Oph with the Short Wavelength Spectrometer (SWS; de Graauw et al. 1996) in mode "AOT 01" (full spectral scan) and twice in mode "AOT06" (deeper scans over a limited wavelength range). In addition, a Long Wavelength Spectrometer (LWS; Clegg et al. 1996) full grating scan ("AOT L01") was taken. The data were reduced in a standard fashion using calibration files corresponding to ISO off-line processing software (OLP) version 7.02, after which they were corrected for remaining fringing and glitches. The resulting SWS spectra are shown in Fig. 1.

The spectra observed by ISO are in good agreement with the ground-based N-band spectroscopy of 51 Oph by Fajardo-Acosta et al. (1993), Walker & Butner (1995) and Sylvester et al. (1996). However, the more complete wavelength coverage, and the higher spectral resolution and signal to noise reveal a wealth of structure hidden in the ground-based data. Shortward of 4.1 μm, the spectrum consists of a smooth continuum, dominated by the photosphere of the central star. A broad absorption due to Brβ can be seen around 2.63 μm. The Brα line at 4.05 μm is filled in with emission (line flux 2.5 10^{-15} W m^{-2}), confirming the emission-line classification of 51 Oph.

A number of strong spectral features due to gas-phase molecules are present in the 4.1–7.5 μm spectral range. We recognise the 4.2–5.4 μm fundamental vibritional band (v = 1–0) of CO, the P and R branches of the ν_2 bending mode of H_2O in the 5.2–7.5 μm range, the 4.1–4.4 μm ν_3 band of CO_2 and the fundamental vibritional band of NO ($\Delta v = 1$) around 5.1–5.9 μm. To further quantify the gas-phase emission lines, we have compared the continuum-subtracted 51 Oph spectrum to a model for gas-phase emission using a single layer, plane parallel LTE code (Cami et al. 2000). A satisfactory fit to our data can be obtained with $T_{\rm mol.}$ = 750–900 K, N(CO) = 10^{20}–10^{22} cm^{-2}. The best fitting model has $T_{\rm mol.}$ = 850 K, $N(H_2O)$ = 4 10^{18} cm^{-2}, $N(^{12}CO_2)$ = 3 10^{16} cm^{-2}, $N(^{12}CO)$ = 3 10^{21} cm^{-2}, $N(^{13}CO)$ = 4 10^{18} cm^{-2}, and $N(^{14}NO)$ 1 10^{18} cm^{-2}. It is shown in Fig. 2. We stress that this fit is not unique and that several other combinations of temperature and column density also give a satisfactory fit. However, we can exclude a large abundance of ^{13}CO. The presence of NO is surprising but is needed in order to fit the emission structure near 5–5.5 μm.

Longward of 8 μm, the spectrum is dominated by solid-state emission from O-rich dust. A strong amorphous silicate feature is present, peaking at 10.3 μm. As was

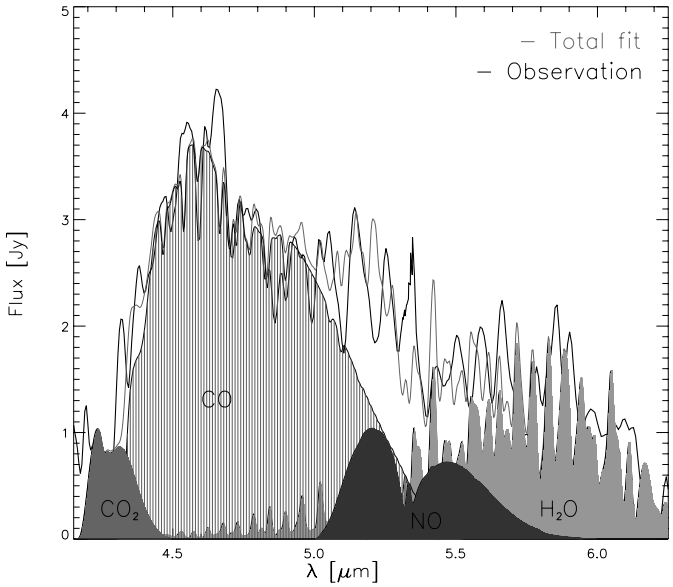

Fig. 2. Continuum subtracted 4–6 μm spectrum of 51 Oph (heavy solid line) compared to a model for gas-phase emission of H_2O, CO, CO_2 and NO at 850 K with $N(H_2O)$ = 4 10^{18} cm^{-2}, $N(^{12}CO_2)$ = 3 10^{16} cm^{-2}, $N(^{12}CO)$ = 3 10^{21} cm^{-2}, $N(^{13}CO)$ = 4 10^{18} cm^{-2}, and $N(^{14}NO)$ 1 10^{18} cm^{-2} (grey line). Contributions of the different gas-phase components are indicated by the shaded area

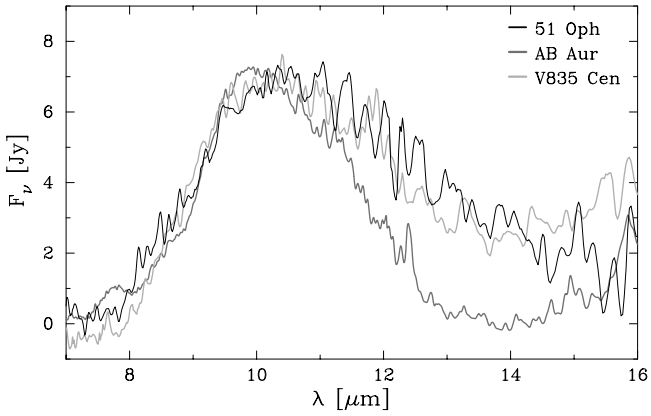

Fig. 3. Continuum subtracted 7–16 μm spectrum of 51 Oph (black solid line) compared to continuum-subtracted ISO SWS spectra of the Herbig Ae star AB Aur (van den Ancker et al. 2000; dark grey curve) and that of the symbiotic star V835 Cen (Mikolajewska et al. 1997; light grey line)

already noted by Fajardo-Acosta et al. (1993) and Sylvester et al. (1996), the long-wavelength shoulder of this feature consists of an almost linear part extending up to 15 μm. We note that this behaviour is incompatible with a purely silicate origin of this feature. A secondary feature, peaking around 11.5 μm and with a width of $\sim$3 μm must be present as well to be able to explain the shape of the 8–15 μm emission complex. A very broad 10 μm band is also seen in the enigmatic object η Car (Morris et al., in preparation).

A second broad bump around 18 μm is present and may be due to amorphous silicates. In the SWS AOT 06 spectrum a narrower ($FWHM \sim 0.4$ μm) peak at 19.2 μm, similar to that seen in stars with emission due to crystalline silicates (e.g. Molster et al. 1999), is superimposed on the broad amorphous silicate feature. 51 Oph was not detected in the LWS scan.

3. Discussion and conclusions

The presence of spectral features in 51 Oph due to hot gas-phase molecules is highly surprising. None of the 47 Herbig Ae/Be stars for which material is present in the ISO data archive shows a 4–8 μm emission complex resembling the one found in 51 Oph. However, such a complex due to emission from hot molecular gas is commonly found in the ISO spectra of O-rich evolved stars on or near the Asymptotic Giant Branch (AGB; e.g. Yamamura et al. 1999; Sylvester et al. 1999).

A further inspection of the ISO data archives confirms our suspicion that the spectrum of 51 Oph is highly unusual for a protoplanetary system: none of the young stars for which spectroscopic data is present shows the 11.5 μm shoulder to the amorphous silicate feature found in 51 Oph, including the isolated Herbig Ae/Be stars, of which 51 Oph is believed to be a member (Meeus et al. 2001; Bouwman et al. 2001). However, comparison of the observed 10 μm profile with archive ISO-SWS data of the symbiotic star V835 Cen (Fig. 3) shows that the 10–15 μm complex in 51 Oph is similar to the one found in this highly evolved system. In fact, the presence of a long-wavelength shoulder to the 10 μm feature is a common feature in the spectra of O-rich AGB objects (e.g. Tielens et al. 1998). It is not observed in other types of stars.

The question arises what is the origin of the circumstellar gas and dust in 51 Oph. In view of the peculiar molecular spectrum (indicative of a large column of hot gas) and the deviating 10 μm silicate band, as well as the sharply dropping mid-IR to millimeter continuum (pointing to a lack of large, cold grains typical for proto-planetary disks) it is interesting to consider the possibility that the circumstellar dust in 51 Oph is "fresh", i.e. recently formed rather than accreted from the interstellar medium and processed in a proto-planetary disk.

One possible explanation for the presence of hot gas and newly formed dust in 51 Oph would be to assume that 51 Oph is a highly evolved rather than a relatively young system. This assumption agrees well with the above main-sequence position of 51 Oph in the HRD. The optical spectrum of 51 Oph, as well as its luminosity, show that a single post-main sequence star can not have created the large amount of circumstellar material we observe. However, the presence of a cool post-main sequence companion may explain the observed properties of the system. We note that a companion to 51 Oph may have been detected: Buscombe (1963) found the radial velocity of 51 Oph to be variable, which could be due to the reflex motion of the companion.

By comparing the optically visible A0 star's $T_{\rm eff}$ of 10 000 K and $L/L_\odot$ of 260^{+60}_{-50} $L_\odot$ with the post-main sequence evolutionary tracks by Schaller et al. (1992), we derive a mass of 3.8 $M_\odot$ and an age of 2 10^8 years for the primary. Using the ISO data and the Hipparcos distance of 131^{+17}_{-13} pc towards 51 Oph we compute an infrared excess of $7.1^{+4.4}_{-2.4}$ $L_\odot$ for 51 Oph. Assuming that both stars in our putative binary system formed at the same time, a lower mass companion should stil be on the main-sequence, limiting its mass to <2 $M_\odot$ if its luminosity is not to exceed the observed infrared excess. This lower mass for the more evolved star in the system is at odds with the mass derived for 51 Oph itself, unless significant interaction between both stars occurred. In addition, it is highly unlikely that an evolved star of less than 7 $L_\odot$ shows such a large amount of circumstellar matter.

Another possibility would be to assume that the companion is more massive than the optically visible A0 star. Any scenario in which the companion would be a red giant or AGB star of comparable mass to the primary is impossible, since such a star would have a luminosity that greatly exceeds 7 $L_\odot$. However, if the companion would be sufficiently massive ($\gtrsim$7 $M_\odot$), it would already have evolved to become a massive white dwarf of very low luminosity. In this scenario, the material observed around 51 Oph today could be caught in remnants of material from the AGB wind of its companion. However, the lack of a significant amount of ^{13}CO in the composition of the circumstellar material argues against this scenario. We conclude that the presence of an evolved companion in 51 Oph is unlikely.

The rapidly rotating ($v \sin i$ = 270 km s^{-1}; Dunkin et al. 1997), emission-line character of 51 Oph has led to an association with the Be stars, who share many of the properties of 51 Oph. However, as pointed out by Waters et al. (1988), circumstellar dust is highly unusual in Be stars. The presence of double-peaked Hα emission in 51 Oph does indicate the presence of a gaseous disk, and the width of the line suggests that this gas is close to the star. It is reasonable to assume that the dust is also located in this disk, at a larger distance from the star. In Be stars, the disk can either be the result of (time-variable) mass loss, or from mass accretion from an evolved companion. However, as pointed out above, the presence of an evolved cool companion is difficult to understand given the luminosity of the dust/gas emission in the infrared. If one accepts that the circumstellar material is due to a recent period of high mass loss from the Be star into a disk, the presence of dust suggests that the amount of gas ejected must have been high enough to shield the UV radiation field of the central star to allow for dust formation. We have fitted the ISO-SWS spectrum using the dust radiative transfer code MODUST (Bouwman & de Koter, in preparation) and find a dust mass of 4 10^{-9} $M_\odot$. This is a factor of 5 higher than the (distance-corrected) value given by Fajardo-Acosta et al. (1993). In this scenario the late-main sequence nature of 51 Oph may be related to the ejection of a large amount of mass, since rapidly rotating early type stars are believed to move closer to their breakup velocity as they evolve (e.g. Langer et al. 1999; Langer 2000).

A more exotic possibility to explain the properties of 51 Oph would be to infer that we are seeing the aftermath of a recent event such as the collision of two gas-rich planets or the accretion of a solid body as the star increases its size at the end of its main-sequence life. New dust could form at the site of the evaporation of the solid body, explaining both the high column of hot gas, the apparent small dust particle sizes and the composition of the silicate dust.

As was already pointed out by previous authors (e.g. Herbig 1994) the problem of separating young stars from their evolved counterparts is non trivial. The case of 51 Oph presented in this *letter* may serve once more to illustrate this difficulty. Even with the extensive data present on this enigmatic object, its evolutionary status remains unclear. New data that is able to resolve the system spatially, as well as a more thorough investigation of the suspected radial velocity variations, may be needed to shed more light on its nature.

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