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High resolution optical spectroscopy of IRAS 09425−6040 (=GLMP 260)*

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ABSTRACT

We present high resolution optical spectroscopic observations of IRAS 09425−6040, a peculiar, extremely red, C-rich AGB star showing prominent O-rich dust features in its ISO infrared spectrum attributed to crystalline silicates. Our analysis shows that IRAS 09425−6040 is indeed a C-rich star slightly enriched in lithium (log(Li/H) + 12 $\sim$ 0.7) with a low $^{12}C/^{13}C = 15 \pm 6$ ratio. We also found some evidence that it may be enriched in s-elements. Combining our results with other observational data taken from the literature we conclude that the star is possibly an intermediate-mass TP-AGB star ($M \gtrsim 3\ M_{\odot}$) close to the end of its AGB evolution which may have only very recently experienced a radical change in its chemistry, turning into a carbon-rich AGB star.

Key words. stars: AGB and post-AGB – stars: individual: IRAS 09425−6040 – stars: abundances

1. Introduction

The evolution of low- and intermediate-mass stars ($0.8 \le M \le 8\ M_{\odot}$) ends with a phase of strong mass loss on the Asymptotic Giant Branch (AGB) phase. The chemical appearance (C-rich or O-rich) of these stars during the AGB phase depends mainly on the progenitor mass and metallicity. Low-mass AGB stars ($M \lesssim 2{-}3\ M_{\odot}$), initially O-rich, can switch to a C-rich chemistry (C/O > 1 in the envelope) after a certain number of thermal pulses and the subsequent dredge-up of C-rich material to the surface of the star. Higher mass stars ($M \gtrsim 3{-}4\ M_{\odot}$), in contrast, remain O-rich during their whole AGB evolution, due to the activation of the "Hot Bottom Burning" (HBB; e.g. Sackmann & Boothroyd 1992; Mazzitelli et al. 1999) process, which prevents the formation of carbon, favouring the production of nitrogen, instead. HBB takes place when the temperature at the base of the convective envelope is hot enough ($T \ge 2 \times 10^7$ K) that ^{12}C can be converted into ^{13}C and ^{14}N through the CN cycle. As a consequence, the $^{12}C/^{13}C$ ratio decreases in the envelope to values close to the CN-cycle equilibrium ratio ($\simeq$3–4). Theoretically, HBB models also predict the production of the short-lived ^7Li through the Cameron & Fowler (1971) mechanism.

The chemistry of the dust in AGB circumstellar shells is also determined by the C/O ratio. Some authors have considered a few carbon stars with circumstellar amorphous silicate dust emission as transition objects between O-rich and C-rich stars on the AGB (e.g. Chan & Kwok 1991; Kwok & Chan 1993). These stars are generally classified as peculiar J-type stars, as they show characteristic low $^{12}C/^{13}C$ ratios, the presence of Li enrichment and no s-process element overabundances in their atmospheres (Abia & Isern 2000), but its evolutionary status is controversial. At present, they are thought to be low-mass AGB stars ($M < 2\ M_{\odot}$) (Abia et al. 2003), but some AGB stars with higher masses ($M \gtrsim 3{-}4\ M_{\odot}$) which are experiencing HBB (e.g. Lorenz-Martins 1996) can show very similar properties.

Remarkably, the only known C-rich AGB star showing strong crystalline silicate emission is IRAS 09425−6040 (=GLMP 260; hereafter I09425). I09425 displays the highest proportion of crystalline silicates (~75%; i.e. only comparable to the Hale-Bopp comet) observed in any source so far (Molster et al. 2001), while the short wavelength part ($\lambda \lesssim 15\ \mu$m) of the ISO spectrum is dominated by deep absorption bands from C-rich gas-phase molecules (e.g. C_2H_2, HCN, etc.). In this paper we present a chemical abundance analysis of this star, based on high resolution spectra obtained during an optical survey carried out on a large sample of massive galactic O-rich AGB stars (García-Hernández et al. 2006). Section 2 describes the optical observations performed and the results obtained. The main physical parameters and the chemical abundances of I09425 are derived in Sect. 3 while its nature and evolutionary stage is discussed in Sect. 4.

* Based on observations collected at the European Southern Observatory (La Silla, Chile), on observations made with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) with the participation of ISAS and NASA, and on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data Archive at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

2. Optical spectroscopic observations

The high resolution optical spectrum presented here was taken on 1997 February 23 with the CAssegrain Echelle SPECtrograph (CASPEC) of the ESO 3.6 m telescope. The integration time was 30 min and we used a TEK 1024 × 1024 CCD with a 24 μm pixel size. We used the 31 lines mm^{-1} grating and continuously covered the spectral range 6000−8300 Å at $R \sim 40\,000$ in about 27 orders, with small gaps in the redder orders. The two-dimensional spectra were reduced following the standard procedure for echelle spectroscopy using IRAF[1] astronomical routines. Note that the few spectral ranges used in the abundance analysis presented in this paper are not significantly affected by terrestrial features. The *S/N* ratio achieved in the final spectrum varies from the blue to the red orders. At ∼6000 Å the *S/N* ratio is 30−40, while at ∼8000 Å the *S/N* ratio is higher than 100.

Based on the available low resolution spectrum (Suárez et al. 2006), the source can be identified as an extremely reddened carbon star with Hα in emission. The steepness of the spectrum is such that no continuum is visible shortwards 5500 Å.

The high resolution optical spectrum of I09425 here discussed is dominated by the presence of multiple CN and C_2 absorption bands. Overimposed, we can still clearly identify some strong atomic lines such as the Li I resonance line at 6708 Å, the K I line at 7699 Å, the Rb I line at 7800 Å and a few atomic lines corresponding to s-process elements. Interestingly, we found that the resonance atomic lines of Li I, Rb I and K I display blue-shifted circumstellar components, which are stronger than the photospheric absorptions, suggesting the presence of an expanding circumstellar envelope around I09425. We derived Doppler velocities of −22.3, −21.2 and −21.8 km s^{-1} from the Li I, Rb I and K I circumstellar lines, respectively. In Fig. 1 the optical spectrum of I09425 from 6680 to 6720 Å is compared with the spectra of other well studied C-rich AGB stars (the N-type star U Hya, the J-type star RY Dra and the "super Li-rich" star IY Hya). The Li I line in I09425 is very strong, but not as much as in IY Hya, indicating that possibly I09425 is not a "super Li-rich" star. In Fig. 1 we can also see the strong blend at 6687.6 Å corresponding to Y I which is very strong as well in IY Hya and in the N-type carbon star (U Hya), but it is completely missed in the J-star RY Dra. The s-process element atomic lines such as Y I at 6024, 6434 and 6793, Zr I at 5955, 6025, 6062, and 6762, Ba I at 6142, La I at 6578 and 7334 and Gd I 7135, among many others, are also very strong in the spectrum of I09425, suggesting that it may be slightly enriched in s-elements (see Sect. 3.1).

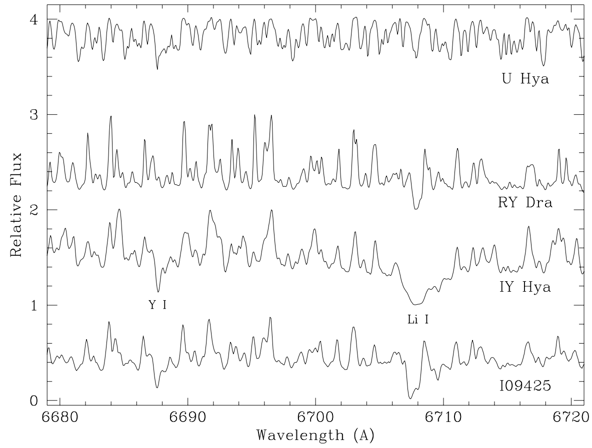

Fig. 1. Spectral region around the Li I line at 6708 Å of IRAS 09425−6040, compared with the same region in three other AGB carbon stars of different type. The continuum level has been placed at the same point (∼6725 Å) in all the spectra. *From top to bottom*: the N-type star U Hya, the J-type star RY Dra, the super Li-rich star IY Hya, and IRAS 09425−6040. Note the strong similarity (except by the very different strength of the Li I line) between the spectrum of IRAS 09425−6040 and that of IY Hya.

3. Data analysis

3.1. Chemical abundances

Very little photometric information is available in the literature about I09425 to estimate its atmospheric parameters. From the available infrared colours and the calibration by Ohnaka & Tsuji (1996), we estimate a very low $T_{\rm eff}$ = 2000 K which seems unrealistic. Synthetic spectra computed with a C-rich model atmosphere with this effective temperature actually result in very strong CN and C_2 absorption bands which are not seen in the spectrum of I09425. This probably indicates that the photosphere of the star is hotter and that infrared colours may be affected by the presence of host dust in the circumstellar envelope. Thus, we computed synthetic spectra with different values of the stellar parameters until a reasonable agreement and consistency was found in the fit of several spectral ranges (6700 Å for Li, 7800 Å for Rb, and 8000 Å for the carbon isotopic ratio). The atmospheric parameters finally adopted were $T_{\rm eff}$ = 2850 K, $\log g$ = 0.0, [Fe/H] = 0.0 and ξ = 2.2 km s^{-1}, which are typical values for galactic carbon stars (e.g. Lambert et al. 1986). The uncertainty in these parameters is high, the most important ones affecting the errors in the abundance determination being $T_{\rm eff}$ (±300 K) and microturbulence (±1 km s^{-1}). The uncertainty in gravity (±0.5 dex) and metallicity (±0.3 dex) do not significantly affect the derived abundances. We have used the grid of model atmospheres for C stars computed by the Uppsala group (see Eriksson et al. 1984 for details). The adopted atomic line list is basically that used in Abia et al. (2001) after some revisions using solar gf-values derived by Thévenin (1990). The molecular line list includes CN, C_2 and CH. The C_2 lines are from Querci et al. (1971) while the CN and CH lists were assembled from the best available data and are described in Hill et al. (2002) and Cayrel et al. (2004).

By using the model atmosphere mentioned above and the synthesis spectral technique, the abundance ratios C/O = 1.01, $^{12}C/^{13}C = 15 \pm 6$ and estimations of the abundances of Li and Rb, namely: log(Li/H) + 12 ∼ 0.7 ± 0.4 and [Rb/Fe] ∼ 0.1 ± 0.3 (which should be taken cautiously, because the lines used are affected by the presence of a circumstellar component) were derived[2]. Our determination of the $^{12}C/^{13}C$ ratio from the optical spectrum is in good agreement with the $^{12}C/^{13}C$ ratio of ∼10 derived by Molster et al. (2001) at sub-millimetre wavelengths. The estimated errors reflect mostly the sensitivity of the derived abundances to changes of the model atmosphere parameters and do not consider possible non-LTE effects, dynamics of the atmosphere, errors in the model atmosphere or errors in the molecular/atomic linelists. The best fit around the spectral region used to derive the Li abundance (6680−6730 Å) is shown in Fig. 2.

[1] Image Reduction and Analysis Facility software is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[2] For details about the technique used, see Abia & Isern (2000), Abia et al. (2001).

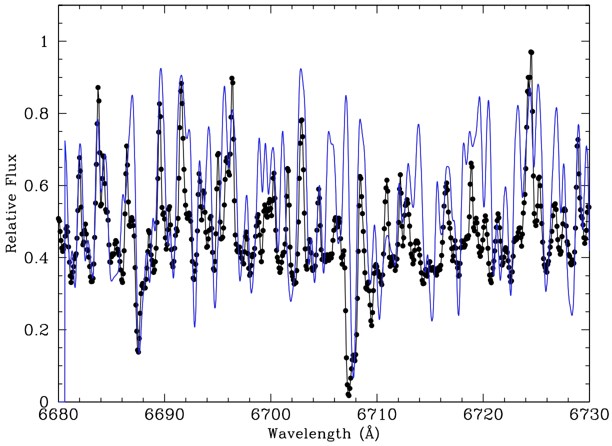

Fig. 2. Synthetic (blue) and observed (black) spectra of IRAS 09425-6040 in the wavelength region around the Li I line at 6708 Å. Note that the lithium line has a clear "blue-shifted" circumstellar component. (This figure is available in color in electronic form.)

From our chemical analysis, we also found that the best fit in the spectral ranges studied is always obtained with a slight over-abundance of s-elements such as Zr, Y, Ba, La, etc., and with a slightly metal-poor model atmosphere. However, the large error bar associated to the derived s-element abundances prevent us to reach any firm conclusion about the possible s-element over-abundance until a more detailed analysis is done.

3.2. Other data

Unpublished optical HST/ACS images taken through the broad band filters *F435W* and *F606W* with several exposure times ranging from 1 to 250 s were also retrieved from the HST Data Archive[3]. We found that I09425 is the brightest source in the field in the *F606W* filter while it is barely detectable in the *F435W* filter. This is consistent with the characterictics seen in the optical spectrum of I09425. In addition, we found that I09425 is a point-like source to HST ($FWHM = 0.09''$).

ISO SWS spectroscopy of I09425 has already been analysed in detail by Molster et al. (2001) where its chemical dichotomy (C-rich and O-rich) became evident for the first time. From the ground-based near-IR photometry taken during the period 1990−1992 and reported by García-Lario et al. (1997) and Fouque et al. (1992) complemented with more recent 2MASS and DENIS data taken in the period 1999−2000, we found a variability amplitude wider than 1.2, 0.9 and 0.7 mag in the J, H and K bands, respectively. This large amplitude suggests that I09425 is likely a long-period (∼500−700 days) Mira-like star. On the other hand, the red IRAS colours indicate that I09425 is a very red star which is probably experiencing a strong mass loss. Consistently, Molster et al. (2001) derived a mass-loss rate of $2 \times 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$ from observations of the pure rotational transitions of ^{12}CO at $J = 1{-}0$, $J = 2{-}1$ and of ^{13}CO at $J = 2{-}1$ at 115, 230 and 22 GHz, respectively.

By integrating the observed flux at all wavelengths, a distance-dependent luminosity of ∼1710 $(\mathrm{D/kpc})^2\,L_{\odot}$ is obtained. I09425 is located in the direction of the Carina star forming region which is at a distance of ∼2.7 kpc (Tapia et al. 2003). If we assume that I09425 is also a member of the Carina complex (and this is supported by the radial velocity derived from our optical spectrum), a total luminosity of ∼12 500 $L_{\odot}$ is derived. According to Blöcker (1995) this would correspond to an AGB star with a core mass of 0.84 $M_{\odot}$, suggesting a relatively massive progenitor ($M \gtrsim 3{-}5\ M_{\odot}$).

[3] They were originally part of the snapshot program 9463 (P.I. Sahai).

4. Discussion

Considering the above results, there are several possibilities to explain the evolutionary status of I09425:

a) I09425 is a low-mass binary carbon star ($M < 2{-}3\ M_{\odot}$) and its O-rich circumstellar shell is the result from previous accretion from a companion star. As proposed by Molster et al. (2001), the O-rich dust could be stored in a massive circumbinary disk. This would be consistent with the strong crystalline silicate emission detected by ISO. However, the observed 12/2.2 μm flux ratio is more consistent with the star being an "intrinsic" (no binary) AGB star (Jorissen et al. 1993) which has very recently experienced a very strong mass loss. Note that binary (extrinsic) AGB S-type stars do not usually show Li enhancements (e.g. Barbuy et al. 1992). It is unlikely that Li could survive during the mass-transfer and subsequent mixing. In addition, no firm evidence for binarity in I09425 nor for any disk structure exists yet.

b) I09425 is a low-mass J-type carbon star. The peculiar chemical abundances of I09425 are rather similar to the J-stars studied by Abia & Isern (2000). J-type stars are preferentially identified as low-mass AGB stars ($M < 2\ M_{\odot}$) on the early AGB (Abia et al. 2003). Some authors have suggested that J-stars could bring up to the surface the C-rich material via a process distinct to the third-dredge−up (e.g. the helium flash) (e.g. Deupree & Wallace 1996). In order to explain the Li and ^{13}C production, a non-standard mixing process, the so-called "Cool Bottom Processing" (CBP) (Wasserburg et al. 1995; Domínguez et al. 2004) is invoked. However, the strong infrared excess observed in I09425 together with the properties of the Mira-like variability argue against an early AGB status for this object. There are no other J-type stars known to exhibit crystalline silicates (see e.g. Yang et al. 2004) which are only observed in high mass loss rate O-rich AGB stars (see e.g. Sylvester et al. 1999).

c) I09425 is a TP-AGB star with a progenitor mass close to the limit for the HBB occurrence (∼3−4 $M_{\odot}$). This interpretation is consistent with the observed Mira-like variability and with the strong IR excess observed, which indicate that the star may be in an advanced stage on the AGB. This would also be consistent with the estimated progenitor mass of ∼3−5 $M_{\odot}$, previously derived from luminosity considerations. Under this scenario, I09425 would be a HBB AGB star which has lost an important fraction of its envelope mass (O-rich) during its evolution, and in which HBB may have recently become deactivated because of the strong mass loss (e.g. Frost et al. 1998) or simply by the ^{3}He exhaustion in the envelope (e.g. Forestini & Charbonnel 1997) but not the operation of the third dredge−up. Note that the probable slight s-element enrichment, as suggested from our chemical analysis, is also in good agreement with the small s-process element enhancement recently found in massive ($M \gtrsim 3\ M_{\odot}$) galactic O-rich TP-AGB stars by García-Hernández et al. (2006). After a few thermal pulses more, and according to the theoretical models, the O-rich AGB star can turn into a C-rich star still showing some Li and a low ^{12}C/^{13}C ratio from the previous HBB epoch (see Lattanzio & Forestini 1999). For some time a mixed chemistry (a C-rich central star and O-rich dust in the envelope) will be observed in its spectrum.

The crystallization of amorphous silicates occurs via the heating and the subsequent cooling of the dust grains. This may occur slowly at low temperature in a long-lived circumbinary disk, under the influence of UV radiation (as in the Red Rectangle, although here the temperature of the central star is so low that the expected production of UV photons is negligible), or quickly in the AGB wind at very high mass loss rates, through high-temperature annealing (Waters et al. 1996; Sylvester et al. 1999). We suggest that this latter mechanism may have operated in the case of I09425 to produce the huge crystalline silicate emission that we now observe.

The observation of stars like I09425 is very improbable because this evolutionary phase is short-lived and extremely rare. The detection of Li and the presence of C-rich gas-phase molecules in the ISO spectrum of the central star (and also the C/O ratio of 1.01) suggest that the change of chemistry has been relatively recent because of Li has not been destroyed and there has been no time to form more complex molecules such as PAHs. The bulk of the previously expelled O-rich material would be now found only farther away from the central star as cooler O-rich dust. Similar observational double-dust chemistry properties are observed in a few transition sources from AGB stars and planetary nebulae (the so-called post-AGB stars), which are interpreted as the consequence of a late TP at the end of the AGB (e.g. Zijlstra 2001). It is tempting to speculate that in I09425 we are observing the same physical process at an earlier stage of evolution. Further observations in the near future may reveal additional surprises and will certainly help clarifying the evolutionary status and main properties of this rather peculiar star, which may be rapidly evolving towards the post-AGB stage.

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