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Two mass-losing carbon stars in the Galactic halo

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ABSTRACT

Observations of two mass-losing carbon stars in the Galactic halo, IRAS 08546 + 1732 and 12560 + 1656, are presented. These objects were discovered serendipitously, and stand out from the usual carbon stars at high galactic latitudes in that they have optical and *IRAS* colours consistent with current mass-loss.

New optical spectra, CO observations, and modelling of the spectral energy distribution and of the CO lines are presented. Luminosities are derived using a period–luminosity relation. From the dust modelling IRAS 08546 + 1732 is found to be at 20 kpc from the Sun (11.3 kpc from the Galactic plane) and has a mass-loss rate of 3.3×10^{-6} $M_\odot$ yr^{-1}. From the CO non-detection we deduce that it is probably oxygen-deficient, corroborating earlier work. IRAS 12560 + 1656 is found to be at 8.0 kpc from the Sun (7.8 kpc from the Galactic plane) and has a mass-loss rate of 1.3×10^{-6} $M_\odot$ yr^{-1}. The detection of the ^{12}CO $J=2$–1 transition in the spectrum of IRAS 12560 + 1656 after an integration time of 10 h makes it probably the longest ^{12}CO integration on a stellar object. The detection itself makes the star one of the most distant stellar objects detected in the CO line. The outflow velocity of 3.2 km s^{-1} is very low, and the stellar velocity is + 88 km s^{-1} with respect to the LSR. Modelling of the CO line implies an oxygen abundance of 0.7 dex below solar.

We examine existing data on the 'faint high-latitude carbon stars' and identify two additional distant, mass-losing, N-type AGB stars. The nature of halo carbon stars is discussed, and suggestions on how to find more mass-losing halo AGB stars are presented.

Key words: stars: AGB and post-AGB – stars: carbon – circumstellar matter – stars: mass-loss – Galaxy: halo – infrared: stars.

1 INTRODUCTION

Since newly born stars have an oxygen abundance which is larger than the abundance of carbon, the existence of carbon-rich objects (defined by having C/O > 1 in the photosphere) indicates that during a certain stage of post-main-sequence evolution carbon is produced in at least a fraction of stars. This evolutionary phase is believed to be the thermal-pulsing asymptotic giant branch (AGB) phase where carbon is produced near the core and added to the convective envelope in some intermediate-mass stars by a process called third dredge-up (Iben & Renzini 1983). The carbon-rich stars associated with this phase are the cool, luminous N-type carbon stars. Characteristics of these stars are that they lose mass at a large rate (10^{-7}–10^{-4} $M_\odot$ yr^{-1}; e.g. Groenewegen 1995; Groenewegen et al. 1997) and usually show Mira or semiregular types of pulsations.

Since the scaleheight of N-type carbon stars is about 200 pc (e.g. Groenewegen et al. 1992), it would be surprising to find carbon stars with a circumstellar shell (characteristic of AGB stars) at more than 1–2 kpc from the Galactic plane. However, two such objects have been discovered serendipitously: IRAS 12560 + 1656 ($b=79°$, $l=312°$; hereafter IRAS 12560) and IRAS 08546 + 1732 ($b=35°$, $l=210°$; hereafter IRAS 08546) (Cutri et al. 1989; Beichman et al. 1990). Little is known of these stars except that they are carbon-rich. However, Cutri et al. and Beichman et al. already noted the unusual location of these two stars in the Galactic halo.

Joyce, Merrill & Gillett (1997, in preparation) determined from infrared monitoring the periods of both stars to be 390 d. This corresponds to luminosities of 5800 $L_{\odot}$, using the period–luminosity relation of Groenewegen & Whitelock (1996) for carbon Miras. As we derive later, these luminosities imply distances from the Sun of 8 and 20 kpc for IRAS 12560 and 08546 respectively.

In the course of the years, several carbon stars at high galactic latitudes have been found already, but most of these are of the CH-type, which are thought to arise from a somewhat lower mass population, and are related to binary evolution (McClure & Woodsworth 1990). The cases of IRAS 08546 and 12560 concern genuinely mass-losing N-type carbon stars. There are few scenarios which can account for the presence of stars of this mass at such great distances from the Galactic plane. They may have been formed in the halo, and could be the progenitors of the few known carbon-rich planetary nebulae (PNe) at high galactic latitudes (Peimbert 1991). On the other hand, it is not inconceivable that we may be glimpsing the remnants of dwarf spheroidals that have been 'harassed' by their encounter with the Milky Way.

In this paper, we perform a detailed study of IRAS 08546 and 12560. New optical spectra (Section 2), CO observations (Section 3), and radiative transfer model fits to the spectral energy distributions (Section 4) and to the CO observations (Section 5) are presented. The results are discussed in Section 6, where several aspects of finding mass-losing AGB stars in the Galactic halo are also mentioned. We end with some conclusions in Section 7.

2 OPTICAL SPECTROSCOPY

The observations were carried out on the night of 1995 February 23 on the 4.2-m William Herschel Telescope at the La Palma Observatory during service observing. The twin-beam intermediate-dispersion spectrograph, ISIS, was used with the R158B grating and a 1124 × 1124 pixel TEK chip to collect moderate-resolution blue spectra of the objects (see Table 1). Data longward of 6600 Å were gathered using the R600R grating and a 1280 × 1024 EEV detector on the red arm of the spectrograph. Details on these are also given in Table 1. To split the beam, a dichroic crossing over at 6100 Å was in place. Exposures were limited to 1800 s or less in order to keep the cosmic ray rate down to an acceptable level and to provide frequent wavelength calibrations. The weather throughout the run was good, yielding a seeing around 1 arcsec.

Table 1 Journal of spectroscopic observations obtained at the WHT.

Object	Wavelength (Å)	Exposure Time (s)
IRAS 08546	3400-6550	6 × 1800
IRAS 08546	6510-7430	6 × 1800
U Hya	3400-6550	2 × 1
U Hya	6510-7430	2 × 1
IRAS 12560	3400-6550	11 × 1800
IRAS 12560	6510-7430	11 × 1800

In all observations the projected entrance slit width was 1 arcsec. The spectral resolution as determined from arc line profile fits was ≈7 and 1.5 Å respectively for the blue and red spectra. The spectral coverage was 3400–6550 and 6510–7430 Å for the blue and red spectra respectively.

The data reduction in IRAF consisted of the transformation of the two-dimensional images to one-dimensional form, and included the steps of bias subtraction, flat-fielding, sky subtraction and wavelength calibration. Finally, spectra obtained at the same wavelength setting were co-added.

The final co-added spectra are presented in Fig. 1. The blue spectrum of IRAS 08546 was too faint to obtain a sufficient signal-to-noise ratio and is not plotted.

2.1 Spectral types

We first discuss the spectral type of IRAS 12560. A comparison was made to the carbon stars displayed in the spectral atlas of Barnbaum, Stone & Keenan (1996). The spectrum shows stronger C_2 bands than any of the stars in their atlas. The heads of the red system near 6672 Å (2, 5), 6760 Å (1, 4) and 6855 Å (0, 3) are clearly visible. The fact

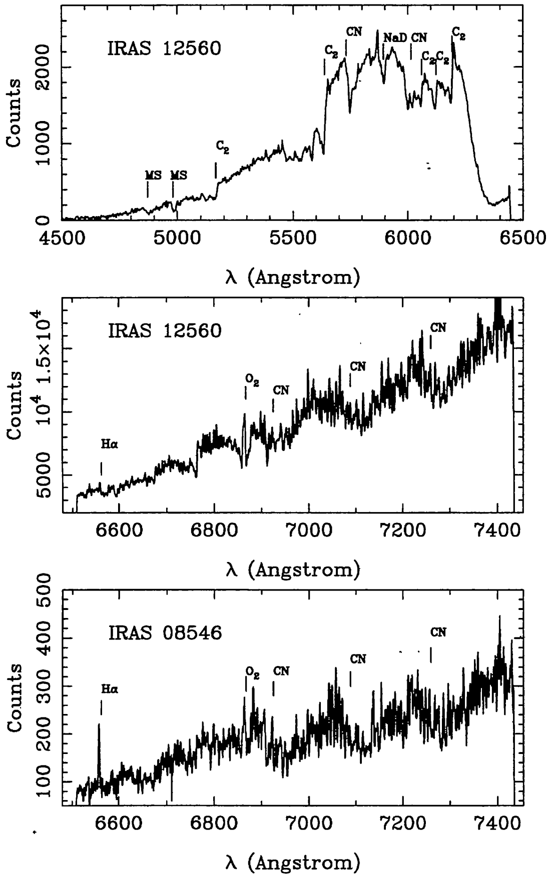

Figure 1. Spectra for IRAS 12560 and 08546. Molecular bands and bandheads are indicated including the atmospheric O_2 line. MS stands for Merrill–Sanford bands (SiC_2).

that the higher vibrational levels are populated suggests that the temperature is not extremely low. The general appearance suggests a temperature not very different from that of most N stars. The isotopic bands in the 6100-Å region are present but not strong, and this also suggests spectral type N. We cannot rule out the possibility that IRAS 12560 is a CH star, but CH stars tend to have stronger isotopic bands and are much hotter. The star displays Merrill–Sanford SiC_2 bands, which probably arise from the great excess of carbon, and do not tell us much about the temperature (Keenan, private communication).

In a recent paper Sarre, Hurst & Lloyd Evans (1996) present observations of two carbon stars with SiC_2 bands in absorption and emission, and make a comparison of the observed bands with recent laboratory work on band assignments. Readily visible in the spectrum of IRAS 12560 are the SiC_2 bands at 4982 and 4871 Å. None of the other bands seem to be present, and they are very weak at best. This may be a resolution effect. In this respect, the spectrum of IRAS 12560 looks similar to that of T Mus in 1994 May (see fig. 1 in Sarre et al.).

The spectral type of the star is C-N5.5: C_2 7 CN 4.5 MS 2, where more abundance indices than usual have been included in order to characterize the star as completely as possible. Beichman et al. (1990) present a 5600–8000 Å spectrum of IRAS 12560. There appear to be no significant changes with respect to our spectrum.

The red spectrum of IRAS 08546 looks qualitatively similar to that of IRAS 12560, which suggests that it is also an N-type carbon star. Note that IRAS 08546 shows strong Hα line emission, indicative of pulsations and/or mass-loss.

2.2 Radial velocities

In order to obtain a reliable radial velocity for the objects, two separate exposures of the radial velocity standard star U Hya were obtained. Unfortunately, the data have been affected by a strong flexure in ISIS on short time-scales, which does not appear to be a simple function of airmass, position on the sky, or timing of the observations.

In spite of the above, we cross-correlated the spectra of our target stars with U Hya, shifting its spectrum to its published heliocentric velocity of -27 km s^{-1} (Barnbaum 1994), and found a local standard of rest (LSR) velocity of 101 ± 20 km s^{-1} for IRAS 12560, and -7 ± 17 km s^{-1} for IRAS 08546. The error represents the error in the cross-correlation only. In view of the above, the true error is likely to be larger. This is evidenced by the fact that if the strong feature seen in IRAS 08546 close to the wavelength of Hα is indeed Hα, then the LSR velocity of IRAS 08546 would be -40 km s^{-1}. From the optical spectra we derive radial velocities with respect to the LSR of 101 ± 40 and -7 ± 40 km s^{-1} for IRAS 12560 and 08546 respectively.

3 CO OBSERVATIONS

The ^{12}CO line observations were obtained at the 30-m IRAM telescope at the Pico Veleta, Spain, on 1996 June 25 (observer HGL) and 1997 January 15–16 (observer MG). On both occasions the instrumental set-up was identical. Two 1.3-mm SIS receivers and two 3-mm SIS receivers (measuring the different polarizations) were used simultaneously and tuned to the CO(1–0) and CO(2–1) lines. The FWHM beam size of the telescope at these frequencies is 21 and 12.5 arcsec respectively. The 1-MHz backend was split into two units, which were connected to the two 1.3-mm receivers, resulting in a velocity separation of 1.3 km s^{-1} and a velocity coverage of ± 332 km s^{-1} around the rest frequency. Similarly, the autocorrelator was split into two units, which were connected to the two 3-mm receivers, resulting in a velocity separation of 0.81 km s^{-1} and a velocity coverage of ± 364 km s^{-1}.

Table 2. Details of the CO line observations obtained at the 30-m IRAM telescope (temperatures are on mean-beam brightness temperature scale).

Object	Line	Exposure Time (min)	T_{sys} (K)	rms (mK)
IRAS 08546	CO(1-0)	260.7	581	13.0
IRAS 08546	CO(2-1)	260.7	1816	23.1
IRAS 12560	CO(1-0)	583.3	457	7.2
IRAS 12560	CO(2-1)	583.3	1149	9.3

Table 2 summarizes the details of the CO line observations, and the spectra are plotted in Fig. 2. The flux scale is mean-beam brightness temperature T_{mb}, which is used throughout this paper. Calibration is done relative to IRC + 10 216. The tabulated exposure time is the sum of the integration times of the two receivers which were active for each line.

The $J = 2$–1 transition in IRAS 12560 is detected at the 4σ level; the $J = 1$–0 transition and the observations of IRAS 08546 proved negative. The peak temperature is 0.035 ± 0.005 K, the expansion velocity is 3.2 ± 0.2 km s^{-1}, and the stellar velocity with respect to the LSR is $+88 \pm 1$ km s^{-1}, consistent with the determination from the optical spectrum (see above).

The CO detection of IRAS 12560 is remarkable in several ways. The total integration time amounts to almost 10 h, which makes it probably the longest integration on a ^{12}CO line in a stellar object. The detection of the $J = 2$–1 line makes it one of the most distant stellar objects detected in ^{12}CO.[1] In Section 5 the CO observations are modelled.

In addition, the expansion velocity is extremely small. Groenewegen et al. (1997) studied nearby carbon Miras, and found that Miras with periods near 400 d typically have an expansion velocity of 10 km s^{-1}. The expansion velocity is not only small relative to similar nearby carbon Miras but also in an absolute sense, cf. the values for short period Miras and semiregular variables in Young (1995), Groenewegen et al. (1996) or Kerschbaum, Olofsson & Hron (1996).

4 FITTING THE SPECTRAL ENERGY DISTRIBUTIONS

In this section the spectral energy distributions (SEDs) of the two stars are modelled with the dust radiative transfer

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[1] Kastner et al. (1993) detected CO in some apparently distant AGB stars in the Galactic plane; their distance estimates are based on kinematics.

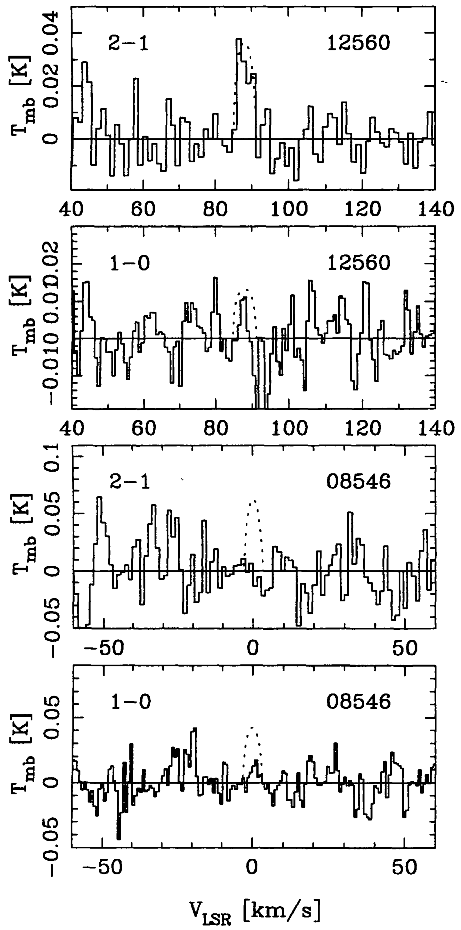

Figure 2. CO $J=2$–1 and 1–0 observations (histogram). Dotted curves indicate model calculations (see Section 5). For IRAS 08546 the calculated profiles have been plotted at an arbitrarily chosen velocity of 0 km s^{-1}.

code of Groenewegen (1993). In this model the radiative transfer equation and the equation of thermal equilibrium are solved simultaneously for the dust in spherical geometry.

The constraints for the fit are, for IRAS 08546, near-infrared and optical photometry and *IRAS* fluxes as quoted in Cutri et al. (1989) ($S_{12}=0.526\pm0.029$ Jy, $S_{25}=0.259\pm0.037$ Jy, $S_{60}<0.10$ Jy, $S_{100}<0.30$ Jy), and, for IRAS 12560, *JHKLMN* multi-epoch photometry by Joyce et al. (1997, in preparation), an $R\sim18$ mag (Beichman et al. 1990), and *IRAS* fluxes as quoted in the Faint Source Catalog (FSC) (Moshir et al. 1989) ($S_{12}=0.792\pm0.055$ Jy, $S_{25}=0.320\pm0.045$ Jy, $S_{60}<0.23$ Jy, $S_{100}<0.35$ Jy). The interstellar extinction towards both objects is assumed to be $A_V=0.1$ mag.

The shape of the SED is fully determined by the effective temperature of the central star, the dust temperature at the inner radius, the dust optical depth at a reference wavelength, and the relative variation with wavelength of the extinction coefficient, Q_λ. For a particular choice of $T_{\rm eff}$, $T_{\rm inner}$, luminosity and Q_λ, the dust optical depth and distance are derived.

A blackbody of 2500 K is used to represent the stellar continuum. The dust temperature at the inner radius is assumed to be 1270 K for IRAS 08546, and 1500 K for IRAS 12560. This is primarily based on the relation between dust temperature at the inner radius as a function of *IRAS* 12- and 25-μm flux-ratio (Groenewegen 1995), and fine-tuned from the model fitting.

The relation between the dust optical depth and physical quantities is

$$\tau_\lambda \sim (\dot{M}_{\rm d}\kappa_\lambda)/(R_* r_{\rm inner} v_\infty) \qquad (1)$$

where $\dot{M}_{\rm d}$ is the dust mass-loss rate, κ_λ is the dust opacity [$\kappa_\lambda=3Q_\lambda/(4a\rho_{\rm d})$, with Q_λ being the absorption efficiency, a the dust grain size and $\rho_{\rm d}=2$ g cm^{-3} the adopted specific density of the dust grains], R_* is the stellar radius in solar radii, $r_{\rm inner}$ is the inner dust radius in stellar radii, and v_∞ is the expansion velocity of the envelope assumed to be constant.

The dust opacity consists of 95 per cent amorphous carbon (optical constants of the 'AC1' species listed by Rouleau & Martin 1991) mixed with 5 per cent silicon carbide (optical constants from Pégourié 1988). The calculations are performed for a grain size of 0.02 μm, using the scattering and absorption properties calculated from Mie theory for spherical grains. The absolute value of the opacity $\kappa_{60\,\mu{\rm m}}=68$ cm^2 g^{-1}.

In the absence of a CO detection for IRAS 08546, an outflow velocity of the envelope equal to that of IRAS 12560 (3.2 km s^{-1}) is assumed. For both stars the luminosity is fixed at 5800 L$_\odot$ from the observed pulsation period and a P–L relation (see Section 1). Given these assumptions, we find dust mass-loss rates of a few 10^{-9} M$_\odot$ yr^{-1} (see Table 3) and obtain distances of 8 and 20 kpc. The optical depths at 0.5 and 11.3 μm are also listed. For other values of the opacity, dust-to-gas ratio or outflow velocity, the derived mass-loss rates scale according to equation (1) above. The best-fitting models and the observations are presented in Fig. 3.

Under the assumption that the outflows are driven by radiation pressure on dust grains, it is possible to derive the total mass-loss rate and the dust-to-gas ratio, Ψ, independently using a modified form of equation $\dot{M}=L/(cv_\infty)$. It is known that in this form this relation does not hold, and that the correct form is

$$\dot{M}=\tau_{\rm F}\frac{L/c}{v_\infty - v_0}\left(1-\frac{1}{\Gamma}\right), \qquad (2)$$

where $\tau_{\rm F}$ is the flux-weighted optical depth (defined as $\tau_{\rm F}=\int F_\lambda \tau_\lambda\,{\rm d}\lambda/\int F_\lambda\,{\rm d}\lambda$), v_0 is the gas velocity at the inner dust radius, and Γ is defined as

$$\Gamma=\frac{3Q_{\rm F}L\Psi v(r)}{16\pi a\rho_{\rm d}cGM_*\,v_{\rm d}(r)}, \qquad (3)$$

Table 3. Parameters derived from model fitting of the SEDs for the two objects.

Object	$\dot{M}_{\rm dust}$ (M$_\odot$ yr^{-1})	Distance (kpc)	$\tau_{11.3}$	$\tau_{0.5}$	$\tau_{\rm F}$
IRAS 08546	4.8 10^{-9}	19.7	0.55	11.2	0.92
IRAS 12560	1.9 10^{-9}	8.0	0.35	7.1	0.81

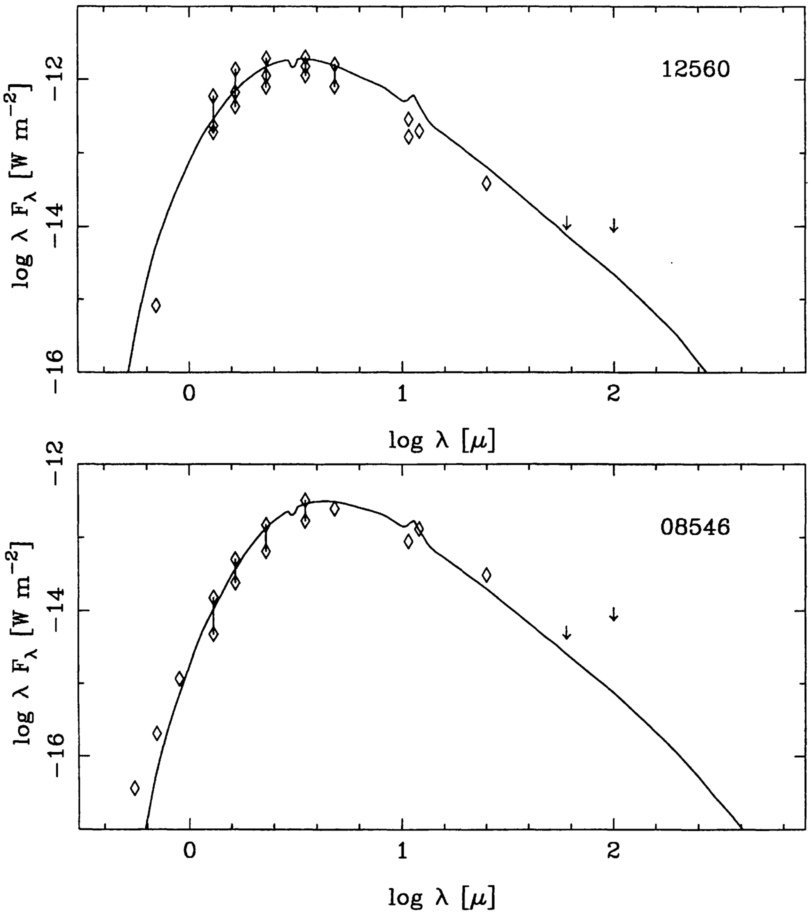

Figure 3. Best-fitting models to the SEDs of IRAS 12560 and 08546. Upper limits are indicated by the arrows. Photomery at minimum and maximum light in the NIR is connected.

where Q_F is the flux-weighted absorption coefficient, L the luminosity, Ψ the dust-to-gas ratio, a the grain size, v the gas velocity, v_d the dust velocity, M_* the mass of the star, and ρ_d the specific dust grain density (see Netzer & Elitzur 1993 and Ivezić & Elitzur 1995). The exact formulation used here, and the iteration process needed to infer the mass-loss rate and dust-to-gas ratio, are explained in Groenewegen et al. (1997). The flux-weighted optical depth follows from the radiative transfer modelling, and is listed in Table 3.

For default values of $a = 0.02$ μm, $\kappa_{60\,\mu\mathrm{m}} = 68$ cm^2 g^{-1} a stellar mass of 0.6 M$_\odot$, and an assumed value of v_0 of 1 km s^{-1}, we find for IRAS 12560 a mass-loss rate of 1.3×10^{-6} M$_\odot$ yr^{-1} and a dust-to-gas ratio of 0.0014, and for IRAS 08546 values of 3.3×10^{-6} M$_\odot$ yr^{-1} and 0.0012 respectively. The values for IRAS 08546 must be considered uncertain, as the expansion velocity is assumed, not measured. The drift velocity of the dust with respect to the gas is found to be 1.6 km s^{-1} for IRAS 12560.

Variations of the assumed parameters to $a = 0.1$ μm, $\kappa_{60\,\mu\mathrm{m}} = 130$ cm^2 g^{-1}, stellar mass of 0.8 M$_\odot$, or $v_0 = 0$ km s^{-1} indicate that the uncertainty in the mass-loss rate is about 30 per cent, and that in the dust-to-gas ratio about 50 per cent.

5 MODELLLING THE CO OBSERVATIONS

We use the molecular line emission code of Groenewegen (1994) to determine the CO abundance in IRAS 12560. The model solves for the gas temperature and the level populations simultaneously. The main heating source is collisions between dust grains and H$_2$ molecules, and the main cooling terms are free expansion and CO line emission. Parameters that enter the code are, amongst others, the distance, mass-loss rate, dust-to-gas ratio, grain size, dust opacity and gas expansion velocity. All these quantities are known. The primary unknown is the abundance ratio of CO/H$_2$, which is determined by fitting the $J = 2$–1 observation. The outer radius of the model is determined by photodissociation, and calculated following Stanek et al. (1995). The best-fitting model is shown in Fig. 2. We find $f_{\mathrm{CO}} = 2 \times 10^{-4}$. This is much lower than the value of about 10^{-3} usually assumed for carbon stars in the Galactic disc. If one assumes that in a carbon star to first approximation all oxygen is locked up in CO, this implies an oxygen abundance relative to hydrogen of 8.00 on a logarithmic scale where $\log H = 12$, or -0.7 dex relative to solar.

There is also an indication that IRAS 08546 is depleted in oxygen: Cutri et al. (1989) suggest the possibility of a severe depletion of oxygen, based on the absence of the CO absorption lines near 2.3 μm. To quantify this possible depletion, we also made model calculations for IRAS 08546. We derive $f_{CO} < 7.5 \times 10^{-4}$, from the requirement that the CO peak fluxes are less than the 3σ noise level. The model is plotted in Fig. 2 at an arbitrarily chosen stellar velocity of 0 km s^{-1}. This is a conservative upper limit based on the noise in a single channel. If we assume an expansion velocity of 3.2 km s^{-1}, a triangular shape for the profile, and hence a 2σ upper limit on the integrated intensity of < 0.20 K km s^{-1}, then we find an upper limit on the CO abundance of $f_{CO} < 5 \times 10^{-4}$. This implies a depletion of oxygen in IRAS 08546 as well.

6 DISCUSSION

We have presented new observations of two peculiar carbon stars in the Galactic halo. There is undeniable evidence that both stars are cool, luminous, N-type AGB stars, and not, e.g., CH stars which are known to exist in the halo. The optical spectra are consistent with spectral type N. The stars show Mira-like pulsations (Joyce et al. 1997, in preparation), from which we derive luminosities that are typical of carbon stars on the AGB. Both stars clearly show excess emission in the infrared due to mass-loss, which is typical for AGB stars.

6.1 Are there more examples of mass-losing AGB stars at high latitudes?

6.1.1 C-rich objects

Carbon stars in the Galactic halo have long been known (Sanduleak 1980; Margon, Aaronson & Liebert 1984). They are sometimes designated faint high-latitude carbon (FHLC) stars. Margon et al. (1984), Mould et al. (1985), Bothun et al. (1991), Green et al. (1994) and Moody et al. (1997) list in total 41 such stars, some of which turned out to be dwarf carbon stars (Green & Margon 1994). Only one of these 41 stars is listed in the FSC, and only one other one (C*07 in Bothun et al. 1991) has a $J-K$ colour which comes close to that of IRAS 08546 and 12560 (2.4 for C*07, 4.2 for 08546, and 3.3 for 12560), indicative of reddening due to circumstellar dust. Using the GIPSY software package (Assendorp et al. 1995), we extracted the *IRAS* 12- and 25-μm data from the *IRAS* data base. The fluxes of C*07 are $S_{12} = 0.19 \pm 0.02$ Jy and $S_{25} < 0.4$ Jy. This low flux level is consistent with the star being absent in the *IRAS* Point Source Catalog (PSC) and FSC. Feast & Whitelock (1992) present two additional infrared measurements, which suggest that this star is a possible variable. C*07 could be a distant, N-type, mass-losing carbon star, but then probably losing mass at a smaller rate than IRAS 08546 and 12560. The $J-K$ colours of the other 40 stars are smaller than 1.3.

Out of 5987 carbon stars in Stephenson's (1989) catalogue, 62 have $|b| > 50°$. From these, 20 are listed in the FSC. Out of those, nine have $S_{12} < 1$ Jy, of which one is listed by Mould et al. (1985) and one by Bothun et al. (1991). Of the other seven, six are known R-type carbon stars, one of which is a known CH star. The reddest object has a $B-C$ colour of only 1.9, which is much bluer than the mass-losing carbon stars under discussion. The remaining star is classified as N-type, and has red *IRAS* colours, but no additional data are available.

Recently, as a by-product of the APM high-redshift quasar survey, Totten & Irwin (1997a,b) presented a list of 48 FHLC stars, of which 29 are new discoveries. Two of the newly discovered stars are listed in the FSC. One is bright at 12 μm (58 Jy), but the other is relatively faint ($S_{12} = 3.2$ Jy), and has red colours; Totten & Irwin (1997b) quote a $B-R$ colour of 6.6, which is close to the colours predicted by the dust model for IRAS 08546 ($B-R=8.3$) and 12560 ($B-R=6.6$). In 1996 August we observed this star (1950 coordinates are RA $= 04^h18^m51\overset{s}{.}9$, Dec. $= +01°22'11''$) with the infrared photometer mounted at the 1.5-m Carlos Sanchez telescope on the island of Tenerife. Its magnitudes at that time were $H = 8.21$ and $K = 6.57$. The $H-K$ colour of 1.64 is very similar to the mean colours of IRAS 12560 (1.57) and IRAS 08546 (2.08). This star could be a distant, N-type carbon star (possibly at 4 kpc, judging from its 12-μm flux compared to that of IRAS 12560) with a mass-loss rate comparable to that of IRAS 08546 and 12560.

Examination of the existing data shows that there are at least two more distant, N-type mass-losing carbon stars in the halo among the FHLC stars known, and possibly more (see Totten & Irwin 1997b).

6.1.2 O-rich objects

OH/IR stars at high galactic latitude are rare. In Sivagnanam et al. (1990), te Lintel Hekkert et al. (1991) and Le Squeren et al. (1992) there is a combined total of about 1000 OH detections. Eight have $|b| > 50°$, but all of them are bright at 12 μm, and may thus be located nearby.

Whitelock et al. (1994) investigated high mass-loss AGB stars in the south Galactic cap. They selected stars with galactic latitude below $-30°$ from the PSC, with high-quality fluxes at 12 and 25 μm, and a flux ratio $S_{25}/S_{12} > 0.5$. Of the 224 selected objects, 61 were found to be Miras.[2] One star in their sample has a flux similar to our two carbon stars, namely W Hyi with $S_{12} = 0.69$ Jy. This is a 281-d Mira of spectral type M4 with a $J-K$ colour of 1.42 (Whitelock et al. 1994). Its heliocentric velocity is $+114$ km s^{-1}, the mass-loss rate is derived to be 1.9×10^{-7} $M_\odot$ yr^{-1}, and its distance is determined to be 7.1 kpc (Whitelock et al. 1994). Their sample contains three additional stars (all M-type) at distances beyond 4.7 kpc, one of which is surprisingly bright at 12 μm. Excluding this one, the 12-μm fluxes are 1.3 and 1.4 Jy, and the mass-loss rates are a few times 10^{-7} $M_\odot$ yr^{-1}.

6.1.3 Future searches

It should be stressed that mass-losing AGB stars in the halo are very rare. Totten & Irwin (1997b) find 48 FHLC stars down to $R=17$, or $V=18$, in 6500 deg^2 of sky. 34 are confirmed N-type carbon stars, and five of those appear to be 'dusty'. This implies a surface density of about 0.0008 dusty carbon stars per square degree.

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[2] It would be interesting to repeat their analysis using the FSC, the completeness limit of which is a factor of 2 lower than that of the PSC.

The area covered by Whitelock et al. (1994) is 10 313 deg^2 and contains three distant, mass-losing O-type Miras, equivalent to a space density of 0.0003 deg^{-2}.

Searches for FHLC stars so far have been performed predominantly in the optical. Near-infrared observations were made as follow-up. The two carbon stars under scrutiny here have been discovered serendipitously at 12 μm. An efficient way of searching for halo carbon and oxygen-rich mass-losing stars similar to IRAS 08546, IRAS 12560 or W Hyi is to use the near-infrared. The mean apparent K magnitudes of IRAS 08546, IRAS 12560 and W Hyi are approximately 9.7, 7.0 and 6.6 respectively. The absolute K magnitudes are -6.8, -7.6 and -7.6 respectively. These stars, which are beyond 7 kpc, almost *saturate*(!) modern near-infrared array detectors. One could probe the Galactic halo out to distances of 230 kpc in a survey down to $K=15$ (and $J=17$–19) if $M_K=-6.8$.

A survey in the infrared out to such distances would sample a volume at least 1000 times larger than the optical studies so far. It is expected that many more distant mass-losing AGB stars in the Galactic halo will be discovered with the infrared surveys DENIS and 2MASS (Epchtein 1997; Skrutskie et al. 1997).

6.2 Evolutionary aspects

6.2.1 *Initial mass*

From the CO observations we derive an underabundance of 0.7 dex below solar for IRAS 12560. Cutri et al. (1989) suggest a severe depletion of oxygen in IRAS 08546, and this is confirmed by the upper limit derived from modelling the non-detection of the CO lines.

From the recent AGB evolutionary calculations of Wagenhuber (1996) we deduce that a star of metallicity 0.7 dex below solar, and with a luminosity of 5800 L$_\odot$, has a core mass of 0.59 M$_\odot$ when it is located on the asymptotic part of the core mass–luminosity relation. If the star has experienced only one thermal pulse, and so-called turn-on effects are important, this is increased to 0.63 M$_\odot$. Again from the Wagenhuber models this implies an initial mass below 2.5 M$_\odot$ for this metallicity. The observed periods for both stars of 390 d are rather typical of carbon Miras in the solar neighbourhood, and suggest that they may have evolved from stars of roughly the same initial mass as most of the carbon stars in the solar neighbourhood, i.e., about 1.5 M$_\odot$ (see Groenewegen, van den Hoek & de Yong 1995).

This then suggests that these stars are not formed in the disc and then ejected (see the scenario discussed below), as the age–metallicity relation in the solar neighbourhood (see Groenewegen et al. 1995) suggests that stars of about 1.5 M$_\odot$ (or an age of about 2 Gyr) have metallicities only slightly below solar. According to the same age–metallicity relation an abundance of 0.7 below solar corresponds to an age of about 11 Gyr, or very small initial masses.

6.2.2 *Dust-to-gas and C/O ratio*

There is a physical upper limit to the dust-to-gas ratio based on the number of atoms that can condense into dust. Using the continuity equation for the gas and the dust, and assuming that the dust is 100 per cent carbonaceous, one may derive that the theoretical dust-to-gas ratio is given by

$$\Psi = f_c(\mathrm{C/O}-1)\,\frac{n_\mathrm{O}}{n_\mathrm{H}}\,\frac{12}{1.4}\,\frac{v_\infty + v_\mathrm{dr}}{v_\infty}, \qquad (4)$$

where n_O and n_H are the number of oxygen and hydrogen atoms, f_c is the degree of condensation of the dust, and C/O is the number ratio of carbon to oxygen atoms in the gas phase. If a constant gas velocity of 3.2 km s^{-1}, a drift velocity of 1.6 km s^{-1}, a dust-to-gas ratio of 0.0014 (see Section 4) and an oxygen/hydrogen ratio of 1×10^{-4} as derived in Section 5 are assumed, then the predicted C/O ratio for IRAS 12560 is 2.1 if $f_c=1.0$, or C/O$=3.2$ if $f_c=0.5$ (see Fleischer, Gauger & Sedlmayr 1995 and Winters, Dominik & Sedlmayr 1994).

We will now estimate if IRAS 12560 can reach these relatively high C/O abundance ratios.

The interpulse time for a star of metallicity 0.7 dex below solar with a core mass of 0.59 M$_\odot$ is 1.0×10^5 yr. The growth of the core mass is expected to be 8.0×10^{-8} M$_\odot$ yr^{-1} (Wagenhuber 1996; a hydrogen abundance of 0.75 is assumed), or 8.3×10^{-3} M$_\odot$ per thermal pulse. If the dredge-up efficiency is 75 per cent (Groenewegen & de Jong 1993), and the composition of the material that is dredged-up contains 22 per cent carbon and 2 per cent oxygen (Boothroyd & Sackmann 1988), then 1.4×10^{-3} M$_\odot$ of carbon and 1.3×10^{-4} M$_\odot$ of oxygen is dredged-up and mixed in the convective envelope per thermal pulse.

For a star of metallicity 0.7 dex below solar, we expect after first dredge-up an abundance of carbon of 5.57×10^{-4}, and an abundance of oxygen of 2.15×10^{-3} (Groenewegen & de Jong 1993). This implies a C/O number ratio of 0.35. If the typical envelope mass is 0.4 M$_\odot$, then it is easily calculated that after the first of the third dredge-up events on the AGB the C/O ratio is increased to 2.2, and after the second dredge-up event is is increased to 3.9.

Although there are uncertainties in this calculation, it does show that it is entirely plausible for a metal-poor AGB star to reach a high C/O ratio, even after a single dredge-up event.

6.2.3 *Halo planetary nebulae*

It is useful to note the similarities and differences between the halo carbon stars and the few PNe that have been found in the halo. The most recent papers on this subject are those by Henry, Kwitter & Howard (1996), Howard, Henry & McCartney (1997) and Kwitter & Henry (1997), who provide abundance studies of halo PNe. In Howard et al. (1997) there are seven halo PNe listed at distances larger than 4.5 kpc. The radial velocities are available for five of them, and are -14, -103, -304, $+30$ and $+196$ km s^{-1}. Distances range from 5 to 17 kpc. All these PNe show subsolar O/H, by factors of 4 to 20. Two have large C/O ratios: 5–6 (K648), 10–23 (BB-1); two unexpectedly have subsolar C/O ratios, and the others have enhanced C/O, but below unity.

The radial velocities, subsolar metallicities and the C/O raitos in some of the halo PNe indicate that the mass-losing, N-type halo carbon stars could very well be the progenitors of the carbon-rich halo PNe.

6.3 The nature of halo carbon stars

The usual argument for the Galactic halo as the site of the formation of high-mass B stars (e.g. Conlon 1993) is an age argument: crudely speaking, the maximum distance travelled from the disc is simply the expected lifetime of a star times the initial velocity. This has been used to infer a halo origin for several B stars, for which the 'flight time' is longer than the theoretical age of these objects. Other halo B stars are suggested to be runaway stars, that moved far into the halo due to a 'kick' obtained during the supernova explosion of their more massive binary companions (Conlon 1993; Little et al. 1995).

This argument cannot apply here; the scaleheight of carbon stars is 200 pc (Groenewegen et al. 1992), and kinematical and other evidence suggests that the majority of carbon stars in the disc evolve from F stars of about 1.5 $M_\odot$ (Groenewegen et al. 1995). Hence the age of the carbon stars involved is long enough to escape from the Galactic plane to arrive at distances in excess of 10 kpc. However, the velocity with which the stars left the Galactic plane must be at least several times 100 km s^{-1} to still have an observed radial velocity of 88 km s^{-1} (in the case of IRAS 12560) at such a large distance from the Galactic plane. This point was also discussed by Cutri et al. (1989) in connection with IRAS 08546. As the velocity dispersion perpendicular to the Galactic plane of N-type carbon stars and their main-sequence progenitors is small, Cutri et al. concluded that IRAS 08546 is indigenous to the Galactic halo, or that it originated in the disc but was ejected into the halo after its formation. As argued above, the latter argument is not plausible, as its metallicity is too low for its initial mass, given the age-metallicity relation in the solar neighbourhood.

So far, the general consensus has been that the halo PNe, described in the previous subsection, should also have formed in the Galactic halo. Other origins of (some of) the FHLC stars have been discussed in the literature. Sanduleak (1980), quoting Shore (1980, private communication), suggests that one particular FHLC star might be associated with the Magellanic Stream. The galactic coordinates of IRAS 08546 and 12560 are very different from that particular star, and so they are not part of the Magellanic Stream.

van den Bergh & Lafontaine (1984) suggest the possibility that halo carbon stars are associated with dwarf spheroidal (dSph) galaxies. Either they may be escapees from dSph galaxies, or they are part of dSphs that are too star-poor to be recognized as such. To test the latter possibility, they performed some star counts in rings centred on one particular halo carbon star. They found no evidence for an undetected dSph galaxy.

Totten & Irwin (1997a) mention the possibility that the halo carbon stars may be associated with dSph galaxies that have been tidally captured by our Galaxy.

There is a caveat of the possible connection of the presently studied carbon stars with dSphs; both stars are *Miras*, and even more carbon-rich Miras may exist in the halo at large distances (Whitelock, private communication). There are, however, no long-period variables known in systems with metallicity below [Fe/H] $= -1$ (Frogel & Elias 1988), including the previously known dSphs. The exception is the Sagittarius dSph, which does contain carbon-rich Miras (Whitelock, Irwin & Catchpole 1996). This system has a metallicity in the range -1.1 ± 0.3 (Mateo et al. 1995), to -0.8 ± 0.2 (Whitelock et al. 1996). The [O/H] abundance of the two PNe recently discovered in Sagittarius (Zijlstra & Walsh 1996) is 0.4 dex below solar (Walsh et al. 1997), which is comparable to that in the single known PN in the Fornax dSph, the next metal-rich dSph at [Fe/H =] $= -1.4$. In other words, if the two carbon Miras under scrutiny here have been part of a dSph system, then their parent dSph galaxy must have been rather massive/luminous to have been able to reach metallities in excess of [Fe/H] $= -1$. The only dSph where at least part of the population seems to have reached these metallicities is the Sagittarius dSph.

Recently, Ibata et al. (1997) presented a calculation of the orbit of Sagittarius. They found an orbital period of 0.76 Gyr. Considering its age, a star like IRAS 12560 could have been ejected up to 3 orbital periods ago. It would be interesting to verify if the present location and radial velocity of IRAS 12560 can be reconciled with this orbit.

7 CONCLUSIONS

We have obtained observations of two examples of the rare phenomenon of halo carbon stars which are presently losing mass. The observations include the CO detection of the most distant stellar object ever taken.

The conclusions can be summarized as follows.

(1) Optical spectroscopy shows both objects to be carbon-rich, and indicates LSR velocities of 101 ± 40 and -7 ± 40 km s^{-1} for IRAS 12560 and 08546 respectively.

(2) The detection of CO line emission in IRAS 12560 provides an accurate LSR radial velocity determination of $+88$ km s^{-1}. The outflow velocity of only 3.2 km s^{-1} is unusually low.

(3) Modelling the spectral energy distributions results in *dust* mass-loss rates of order a few times 10^{-9} $M_\odot$ yr^{-1}.

(4) Modelling of the line emission in IRAS 12560 shows the abundance of CO to be 5 times lower than for normal disc carbon stars. This, and the low outflow velocity, are probably the result of a very low initial metallicity, which is estimated to be 0.7 dex below solar.

(5) From existing data on faint halo AGB stars we identify two additional possible halo mass-losing carbon stars and one halo oxygen-rich mass-losing AGB star.

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