Astron. Astrophys. 285, 179–184 (1994)

ASTRONOMY
AND
ASTROPHYSICS

Nebular emission lines in IRAS 10215−5916*

P. García-Lario[1,2], A. Manchado[3,4], M. Parthasarathy[5], and S. R. Pottasch[6]

[1] INSA; ESA IUE Observatory **. VILSPA. Apartado de Correos 50727, E-28080 Madrid, Spain
[2] Laboratorio de Astrofísica Espacial y Física Fundamental. Apartado de Correos 50727, E-28080 Madrid, Spain
[3] Astronomy Department, University of Illinois, 1002 W. Green Street, Urbana, IL 61801, USA
[4] Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain
[5] Indian Institute of Astrophysics, I-560034, Bangalore, India
[6] Kapteyn Astronomical Institute, Postbus 800, NL-9700 AV Groningen, The Netherlands

Received 26 February 1993 / Accepted 9 November 1993

Abstract. From low and high resolution spectroscopic observations of IRAS 10215−5916 we have discovered the presence of nebular emission lines in this G-type supergiant star in the post-AGB stage. From its high resolution spectrum we derived an expansion velocity of 17 km s^{-1} for the shell, similar to the values usually observed in planetary and proto-planetary nebulae. The images taken in the near infrared show that IRAS 10215−5916 is slightly extended and asymmetric. Although we cannot rule out a possible binary nature for the central star of this IRAS source, in which a hot component could be the responsible for the observed nebular emission, no indications of binarity have been found so far. We suggest that the observed spectrum and morphology could be produced by the asymmetric mass loss of a single star in the post-AGB phase. Post-AGB mass loss can play a fundamental role on shortening the transition time towards the planetary nebula stage and favour the formation of the bipolar structures commonly observed in evolved planetary nebulae. In this sense, it is shown that this mass loss is more intense and frequent for massive progenitors of PNe.

Key words: stars: emission lines – stars: mass loss – stars: IRAS 10215–5916 – stars: supergiants – stars: AGB, post-AGB – infrared: stars

1. Introduction

Over the last decades there has been a strong controversy about the nature and evolutionary stage of a certain number of intermediate-type supergiant stars, some of them located at a high galactic latitude. With the advent of IRAS data Parthasarathy & Pottasch (1986) discovered that these stars show a strong infrared excess, which they explained as the consequence of the presence of cold circumstellar envelopes. The infrared colours and dust masses inferred from IRAS data are very similar to those observed in young planetary nebulae (PNe). Therefore, they concluded that they could be post-AGB stars and suggested that the supergiant appearance was the result of a temporary extended state of their atmospheres on their way to become a PN after the end of the AGB phase.

During the last years many of these expanding envelopes have been detected in CO (Likkel et al. 1987, 1991), supporting the evolutionary connection between these stars and PNe. However, abundance analysis are not conclusive (Luck & Bond 1989) and, although they are found to be slightly metal deficient and show carbon and oxygen overabundances compared to iron, the s-process elements do not show any enhanced abundance, in contrast with the overabundances found in AGB stars.

With the help of IRAS data it has been possible to recognize new stars in this short transition phase, because of their characteristic infrared colours (Manchado et al. 1989; Volk & Kwok 1989). The variety of spectral types found suggests that they form a continuous sequence from late-type M and K stars to A and B stars (some of them with emission lines). This has been interpreted as the consequence of the increasing effective temperatures of the central stars in their evolution to the PN stage. One of these new post-AGB stars is IRAS 10215−5916 (Parthasarathy 1989), a G-type supergiant star for which we present new observational results in this paper.

2. Observations and results

IRAS 10215−5916 (= CPD $-58^0 2154$ = AFGL 4106) was observed in March 1988 and June 1990 with the 3.60 m ESO telescope and in February 1990 with the 1.5m ESO telescope, both at La Silla (Chile), with low resolution spectroscopy. All the spectra are very similar. In Fig. 1 we show the spectrum taken with the 3.60 m ESO telescope in March 1988 with EFOSC (ESO

Send offprint requests to: P. García Lario

* Based on observations collected at the European Southern Observatory, La Silla, Chile

** Affiliated to the Astrophysics Division, Space Science Department, ESTEC

1994A&A...285..179G

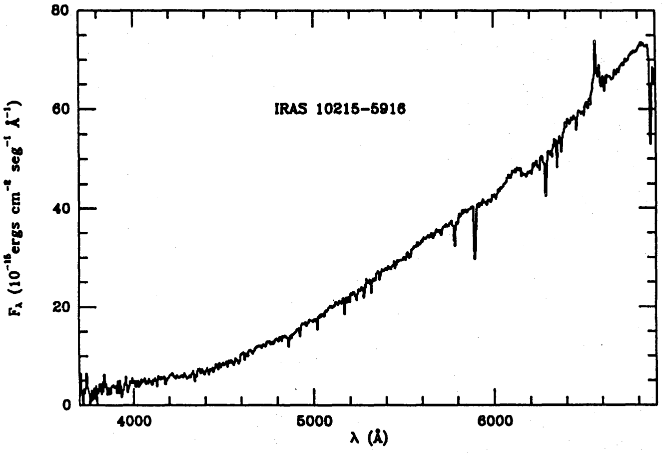

Fig. 1. Low resolution spectrum of IRAS 10215−5916 taken with the 3.60 m ESO telescope at La Silla (Chile) in March 1988

Table 1. Relative intensities compared to Hα = 100

Line	Intensity
6548 [N II]	50
6563 Hα	100
6584 [N II]	123
6678 He I	$\leq$5.4
6717 [S II]	7.7
6731 [S II]	8.4

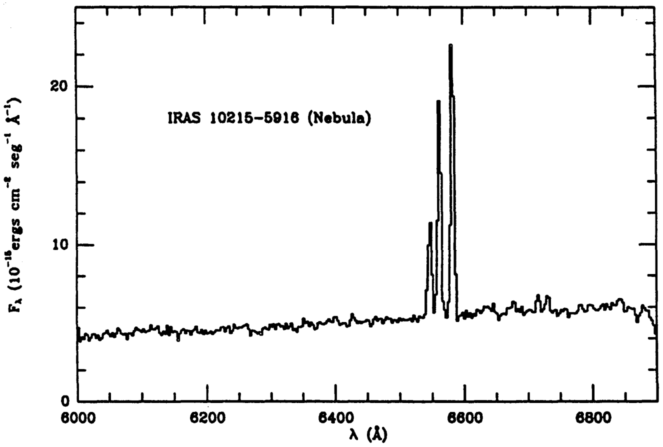

Fig. 2. Nebular component detected in the low resolution spectrum of IRAS 10215−5916 taken in February 1990

Faint Object Spectrograph and Camera) and an RCA CCD as detector which covers a spectral range between 3700 Å and 7100 Å with an effective spectral resolution of 6.9 Å. The exposure time was 300 s.

It shows a bright optical counterpart (m_V~9), whose coordinates are coincident within a few arcseconds ($\Delta\ \alpha$ = 3”, $\Delta\ \delta$ = 2”) with the IRAS coordinates. The spectrum shows a red continuum and spectral characteristics corresponding to a G-type supergiant in which a weak but broad Hα emission is clearly visible, while the rest of Balmer lines are in absorption. The feature in the red wing of Hα could be [N II] λ 6584 Å but more observations were needed to confirm this.

With this intention we took a new spectrum in February 1990 with the 1.5 m ESO telescope. We used the Boller & Chivens Spectrograph and again an RCA CCD as detector with a similar spectral range and spectral resolution (4.8 Å), but this time with a longer exposure time (900 s). The central star saturated the CCD, but it was possible to detect a slightly extended halo (< 3”) of asymmetric nebular emission to the east of the central star which is shown in Fig. 2. This nebular component includes not only the forbidden nebular lines of [N II] at λ 6548 and λ 6584 Å , but also the [S II] $\lambda\lambda$ 6717, 6731 Å doublet, together with Hα at λ 6563 Å and a possible weak emission of He I at λ 6678 Å. A list of the emission lines found with their relative intensities compared to Hα is given in Table 1.

High resolution spectroscopy was also performed with the 1.4 m CAT telescope at the same observatory in February 1990, with the Coude Echelle Spectrograph (CES). The resolving power was R = 50000, which corresponds to an effective spectral resolution of 0.13 Å around Hα (equivalent to 6 km s^{-1} in velocity) and the result is shown in Fig. 3. The bright emission coming from the central star shows the presence of many absorption lines, characteristic of a G-type stellar continuum, together with a weak but broad Hα emission over a photospheric absorption but, again to the east of the central star, it is possible to extract a weak nebular component which is also shown in the same figure, with a quite different appearance.

This nebular component shows the characteristic double-peaked structure, more clearly seen in the forbidden nebular lines corresponding to [N II], which are generally observed in expanding envelopes. The separation between the peaks in emission corresponds to an expansion velocity of V_{exp} = 17±2 km s^{-1}, similar to those observed in other known proto-PNe and PNe and to the expansion velocities found in other post-AGB stars derived from CO data.

We also took several high resolution spectra in other spectral ranges in order to derive the chemical abundances in IRAS 10215−5916, but the results of this analysis will be presented elsewhere.

Near infrared photometry was obtained at the 1 m ESO telescope with an InSb detector, an aperture of 15” and a *chopping* amplitude of 30” in May 1990. The near infrared colours found (J = 4.56, H = 3.52, K = 3.00, L’ = 2.50, M = 2.68) compared to the IRAS fluxes (F_{12} = 200 Jy, F_{25} = 1750 Jy, F_{60} = 850 Jy and F_{100} = 180 Jy) indicate that the near infrared emission is coming mainly from the central star, but there is a significant contribution of hot dust (about 1000 K) which must be

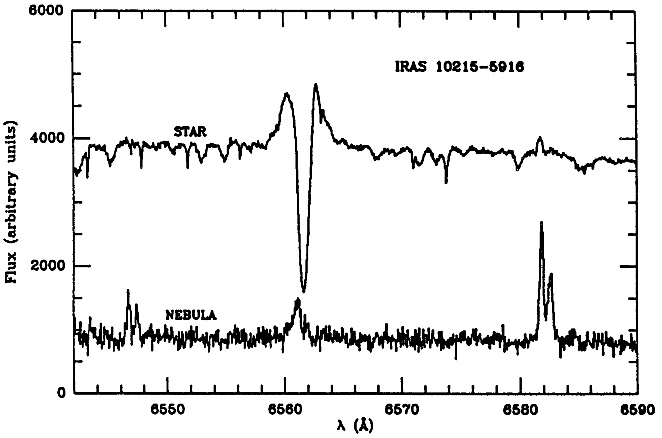

Fig. 3. High resolution spectrum of IRAS 10215−5916 taken with the 1.4 m CAT telescope at La Silla (Chile)

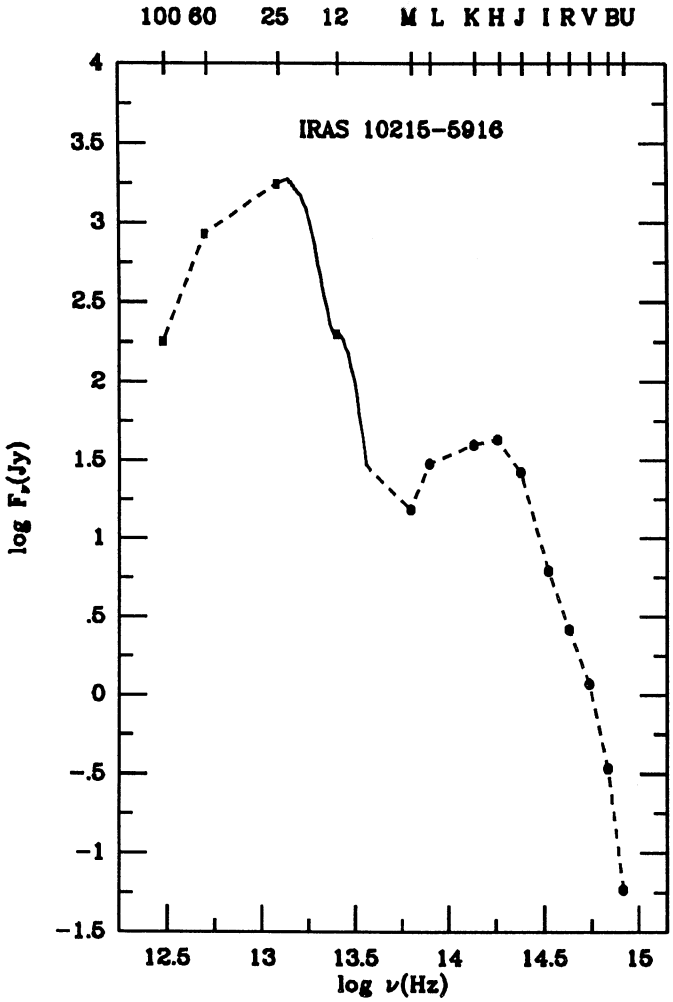

Fig. 4. Optical, near infrared and IRAS photometry, together with the IRAS Low Resolution Spectrum (solid line)

the result of recent mass loss. The best fit for the far infrared IRAS data corresponds to a black-body emission at 180 K. Our near infrared data agree within the errors with the results found in November 1987 by Hrivnak et al. (1989). This is consistent with the low variability index (6%) quoted by IRAS. The global energy distribution is plotted in Fig. 4. Together with the IRAS photometry and our near infrared data we have plotted the optical photometry obtained by Hrivnak et al. (1989) and the LRS spectrum, which shows a small emission around 10 μm, probably due to silicate grains present in the circumstellar envelope.

Near infrared images were taken with the 2.2 m ESO telescope at La Silla in February 1990 in the J, H and K standard bands using IRAC (InfraRed Array Camera) in its 32×32 InSb detectors version, with a pixel scale of 0".3 / pixel. These images, shown in Fig. 5, confirm the presence of a slightly extended and asymmetric structure with a total extension of less than 3". The emission clearly extends to the north of IRAS 10215−5916, with a small tail of emission to the east, and a much fainter one to the west. The north-east emission probably corresponds to that observed in our optical spectra (note that the slit was always oriented in the E-W direction). This tail is specially remarkable in the J band, which is the best tracer of ionized gas, but it is also present in the H and K images. If this emission is produced by the hot dust surrounding IRAS 10215−5916, it means that the mass loss has recently been more intense in certain privileged directions.

3. Discussion

The integrated luminosity of IRAS 10215−5916, combining the optical photometry (UBVRI) obtained by Hrivnak et al. (1989) with the infrared data, and extrapolating towards longer wavelengths, is

$$L = 1.13\ 10^{-2}\ d(pc)^2\ L_\odot \qquad (1)$$

Assuming a luminosity of 5000 $L_\odot$, which is the mean luminosity found in post-AGB stars belonging to the population of the bulge (van der Veen & Habing 1990; García-Lario 1992), we can derive a distance of 0.67 kpc. This small distance means that most of the reddening which is clearly seen in the optical spectrum must be of circumstellar origin.

However, Hrivnak et al. (1989) suggested a distance of $\sim$ 2 kpc, because the source is located in the direction of the Carina complex and it might be associated with it, but this would lead to an extremely high luminosity of $L \sim 45000\ L_\odot$, which seems quite unrealistic for a post-AGB star, although reasonable for a genuine G-type supergiant. In this sense, the distance derived from the Na I D absorption line gives an even larger estimate of d = 3.3 kpc, but this must only be considered as an upper limit, as a considerable fraction of this absorption may be of circumstellar origin.

On the other hand, the radial velocity of IRAS 10215−5916 was derived from the analysis of the emission lines found in the high resolution spectrum (more adequate than the photospheric absorption lines to derive the systemic velocity). We obtained a

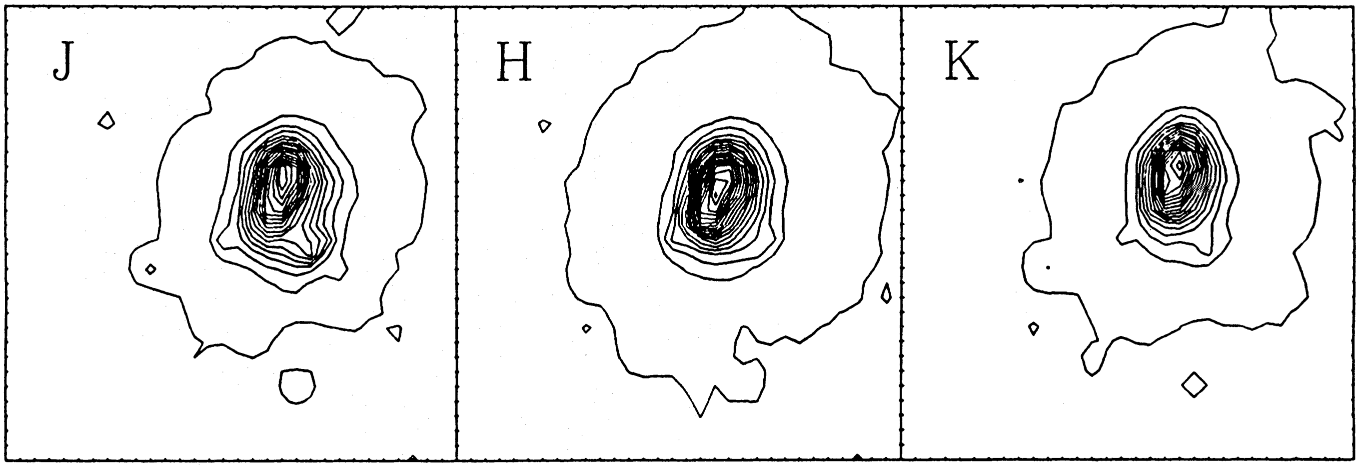

Fig. 5. Contour level maps of the J, H and K near infrared images of IRAS 10215−5916 taken with the 2.2 m ESO telescope at La Silla (Chile) showing the extended structure of this object. The size of each map is 10" × 10". North is down and east at the right. The scale for the levels is linear

value of $V_{LSR} = -40 \pm 5$ km s^{-1}, which is a high radial velocity for a G star in the galactic plane. This favours the hypothesis of IRAS 10215−5916 belonging to the old disk population and thus, in an evolved evolutionary stage. Moreover, a preliminary analysis of the high resolution spectra suggests that IRAS 10215−5916 is relatively metal poor ([Fe/H] < -1.0), as found in other post-AGB stars.

At a distance of 0.67 kpc, the combination of the apparent size of the extended emission observed in IRAS 10215−5916 and the expansion velocity derived from our high resolution spectrum gives an upper limit for its kinematic age of 560 yrs.

The IRAS colours, global energy distribution, chemical abundances and kinematics are all consistent with the evolutionary interpretation of IRAS 10215−5916 being a star in the post-AGB phase, for which the mass loss has not completely stopped after the end of the AGB a few hundred years ago. As the near infrared photometry confirms, mass loss is probably still taking place producing the characteristic near infrared excess usually observed in other post-AGB stars (Manchado et al. 1989; García-Lario et al. 1990), while the far infrared excess would be the result of the mass lost during the AGB phase.

If the emitting dust grains are in radiative equilibrium with the central source, we can assume that most of them are located at a distance to the central source given by the equilibrium radius r_e (see Phillips et al. 1990; García-Lario et al. 1991, and references therein)

$$\frac{r_e}{(\mathrm{pc})} = 44.55\ T_d^{-5/2} \left(\frac{L}{L_\odot}\right)^{1/2} \qquad (2)$$

where T_d is the dust temperature derived from IRAS data and L is the luminosity of the central star. This, of course, is only a crude approach to the problem, as we are assuming a single temperature for the dust in the envelope, spherical symmetry, and a determined size, chemical composition and emissivity for the dust grains.

From this equation we obtain $r_e = 0.0072$ pc, which combined with a typical expansion value for the slow wind in the AGB phase of 10−15 km s^{-1}, as it is commonly observed in OH/IR stars, provides an estimation for the age of the envelope of only 500 − 700 years. Note that we cannot take the expansion velocity of 18 km s^{-1} derived from the nebular emission lines to derive the kinematic age of the envelope, as this corresponds to the post-AGB fast wind.

If we assume that most of this circumstellar material now emitting in the far infrared was ejected in a short lapse of time at the end of the AGB, as models predict (Bedijn 1987), this confirms that IRAS 10215−5916 entered the post-AGB phase around 600 years ago, as we have previously derived from the optical data.

In order to discern the nature of the ionization field (shocks or photoionization), we have made use of a diagnostic diagram, e.g. Cantó (1981). In this diagram the ratios Hα/[N II] and Hα/[S II] indicate clearly that photoionization is the cause of the formation of the forbidden lines. The electronic density n_e in the nebula surrounding IRAS 10215−5916 can be derived from the ratio between the lines forming the [S II] doublet at 6717 Å and 6731 Å, indicating $n_e = 1600$ cm^{-3}, similar to the usual densities found in evolved PNe. We tried to estimate the He^+/H abundance from the ratio He I (6678 Å)/Hα, but we found a very high value of 0.37, which seems unrealistic, probably as a consequence of the uncertainties in the intensity of the He I 6678 Å line, which is extremely faint in the nebular spectrum.

The spectral type of IRAS 10215−5916 has been redetermined from our low and high dispersion spectra. It is found to be a G2 I spectral type. The photometric observations in UBVRIJKL made by Hrivnak et al. (1989) also result in a spectral type around G2 − G5 I. Although nebular emission lines are present in proto-PNe and some post-AGB stars with hotter spectral types, like in the case of BQ[ ] stars and a few A and F stars recently detected by IRAS, this is the first case in which nebular emission lines are observed in a G-type supergiant recognized as a post-AGB star in the literature. This is puzzling because one should not expect to detect an ionized nebula surrounding a star with such a low effective temperature.

Two possible scenarios can explain the presence of this nebular component. In the first one, the forbidden emission lines are due to the presence of a hot companion, invisible in the optical range, which could only be detected in the UV, if the extinction due to the circumstellar dust is not too high. IRAS 10215−5916 could represent a similar case to HR 8752 (Stickland & Harmer 1978) or HD 4817 (Cassatella & Smolinski 1991), also late-type stars with forbidden emission lines. In both cases, IUE data have been able to demonstrate the presence of a hot companion by fitting the continuum emission and the spectral features observed in the ultraviolet.

In the second one, the post-AGB mass loss is asymmetric, as the near infrared images suggest. Small inhomogeneities as *active regions* in the thin hydrogen layer surrounding the helium core of the AGB remnant would produce a partial ionization of the envelope, producing sporadic mass loss events, so that ionizing photons coming from the inner layers of the atmosphere of the central star can reach the outer envelope only through these *active regions*. Although hot regions on the star can also emit a strong UV continuum producing a spectrum resembling that of an early-type star, we expect the observed UV luminosity to be considerably lower in this case, as we would only see a fraction of the total flux emitted by the inner core. Thus, only a detailed analysis of the UV spectrum can discriminate between both scenarios. Alternatively, the presence of a hot companion can only be unambiguously confirmed by detecting possible eclipse effects in the UV or by searching for radial velocity variations with high resolution optical spectra.

In order to exclude or confirm one of these scenarios we have searched for radial velocity variations in the photospheric lines present in our high resolution spectra. These spectra were taken on three consecutive days during February 1990 and consist of sets of several exposures at different wavelength ranges each day. The mean radial velocities found are, respectively, $V_{LSR} = -43 \pm 3$, -38 ± 3 and -45 ± 3 km s^{-1} for each of these days. The velocities derived from Si II lines at 6347 Å and 6371 Å are slightly different. Therefore, the average velocity on the last day of observation is slightly higher. However, and even considering this effect, there are no clear indications of a periodic velocity variation, and the values found are consistent with a single average value of -42 km s^{-1}, in perfect agreement with the systemic velocity derived from the analysis of the nebular emission lines.

Although the time scale of the measurements is short, the results found do not confirm the presence of an invisible hot companion. Under the binary assumption one should expect to find either periodic velocity variations in the photospheric absorption lines, as a consequence of the translation of the G-type star around an invisible close companion, or deviations between the radial velocities derived from the photospheric absorption lines and those derived from the nebular emission lines, which give us information about the systemic velocity. The absence of periodic velocity variations in the photospheric absorption lines could be explained as due to the fact that, unfortunately, we only have measurements covering a time lapse of only 3 days. However, it is more difficult to explain the coincident velocities found both from the photospheric absorption lines and from the nebular emission lines. This, assuming the binary hypothesis, can only be explained if we are seeing the binary system pole-on. In this case, on the other hand, and if we assume that the reddening is mainly circumstellar and due to the presence of a circumstellar disk in the plane of rotation, the hot companion should be easy to detect in the UV range.

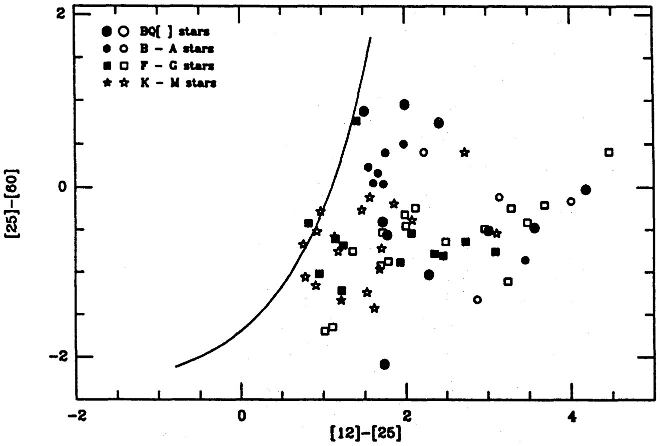

Fig. 6. IRAS two-colour diagram where we show the position of known post-AGB stars with different spectral types. Filled symbols indicate the presence of Hα emission

A peculiar feature observed in IRAS 10215−5916 is the presence of a broad Fe I emission at 6380.7 Å. The width of this emission is 16.6 Å, which corresponds to 780 km s^{-1} at this wavelength. This broad emission is clearly seen in the high dispersion spectra and marginally in some of the low resolution spectra. The presence of such a broad emission suggests that it may be arising from a complex high velocity field associated to a bipolar disk geometry, as iron emission lines are known to be formed in the dense gas which is expected to be found in this kind of circumstellar disks. Broad 6380.7 Å and Hα lines are also seen in HD 101584 (Parthasarathy et al. 1993) for which CO and OH observations show evidences of a bipolar geometry (Trams et al. 1990; te Lintel Hekkert et al. 1992).

A study of the distribution of post-AGB stars with different spectral types in the IRAS two-colour diagram can help us to try to find an answer to the question addressed in this paper. It is now well known that mass loss is still active after the end of the AGB, although at a much lower rate than during the preceding phase. These mass loss processes seem to be sporadic events with a variable intensity and duration and are much more frequent and intense in high mass progenitors of PNe and in the hottest spectral types. This is shown in Fig. 6, where we have plotted the location in the IRAS two-colour diagram of a sample of known post-AGB stars with different spectral types.

While Hα emission is present in all the BQ[ ] stars in our sample and in the majority (7 out of 11) of the post-AGB stars with A or B spectral types, this emission is present in only 43 % (12 out of 28) of the stars with F or G spectral types, and the percentage drops to 11 % (only 2 out of 18) when the spectral types are K or M. Moreover, the intensity of this emission is much stronger and violent in those stars located in the upper part of the diagram (usually A and B stars), which is associated with massive progenitor stars (García-Lario 1992).

On the other hand, this is the region of the diagram where type I PNe, most of them showing a bipolar morphology, are located, which are also suspected to be the result of the evolution of massive progenitors. If the evolution in the IRAS two-colour diagram after the end of the AGB phase takes place, in a first approximation, at a constant value of [60]−[25] (Bedijn 1987), these type I PNe should be the result of the evolution of massive progenitors showing strong mass loss rates in the post-AGB phase.

It has been argued that the bipolar structures observed in PNe are the result of the presence of invisible companions which produces the formation of an equatorial disk which collimates the outflow ejected by the post-AGB star. However, if we assume that binary stars are uniformly distributed throughout the IRAS two-colour diagram we cannot explain the absence of bipolar PNe in the lower part of the diagram, where we expect to find only low mass PNe and low mass post-AGB stars.

All these arguments favour the possibility of a connection between post-AGB mass loss and the formation of bipolar structures, without the assumption of a binary model. Further efforts to discriminate between these possibilities should be made.

4. Conclusions

The presence of nebular emission lines in the circumstellar envelope of IRAS 10215−5916 cannot be explained at the moment as the consequence of the presence of an invisible hot companion. On the other hand, IRAS 10215−5916 is not hot enough to ionize its surrounding nebula in its present state. This means that, either the mass loss process is asymmetric and follows an irregular behaviour in the form of sporadic mass loss events of variable duration, or the star was hotter in the recent past than it is currently.

Evidences of strong spectral changes in the lapse of only a few years have been observed in other objects which are suspected to be in the post-AGB stage. The spectral type of FG Sge, for instance, changed from B4 I in 1955 to F6-7 I in 1980 (Montesinos et al. 1990). However, no evidence of possible spectral changes have been found so far in IRAS 10215−5916 since it was first observed in 1988.

The small photometric variations observed in post-AGB stars, the presence of hot dust in their envelopes and the variable Hα emission found in many of them indicate that the mass loss does not completely stop after the end of the AGB, but occurs in the form of sporadic mass loss events during the post-AGB phase. In the case of IRAS 10215−5916, it seems that the end of the strong mass loss phase took place around 500 years ago. Now, the star is in the post-AGB phase, still undergoing mass loss, as the near infrared excess and the presence of Hα emission confirms, but at a much lower rate.

In many cases, high velocity outflows are also found, as can be deduced from the width of the Hα emission. Asymmetric mass loss during this post-AGB phase could lead to the formation of bipolar structures and other irregular morphologies usually observed in evolved PNe, as an alternative to the usual interpretation, which assumes a binary nature for the central stars of bipolar PNe. It can also play an important role in shortening the transition times towards the PNe stage. This could explain the existence of very low luminosity PNe, which are not understood under the present theoretical models.

IRAS 10215−5916 is only a new step in our knowledge of the short transition phase which precedes to the formation of a new PN. The results here presented confirm the connection between these intermediate-type post-AGB stars and proto-PNe and PNe. A detailed abundance analysis of these stars is necessary, however, to confirm unambiguously their evolutionary stage, as well as a monitoring program of a wide sample of them to study the evolution of these mass loss processes with time and its possible dependence on the initial mass of the progenitor star.

Acknowledgements. This research was partially funded through grant PB90-0570 from the Dirección General de Investigacioń Científica y Técnica of the spanish Ministerio de Educación y Ciencia.

References

Bedijn, P.J.: 1987, *A&A*, **186**, 136

Cantó, J.: 1981 in *Investigating the Universe* (Reidel), p. 95

Cassatella, A., Smolinski, J.: 1991, *A&A*, **250**, 365

García-Lario, P.: 1992, *Ph.D. Thesis.* Univ. La Laguna (Spain)

García-Lario, P., Manchado, A., Pottasch, S.R. et al.: 1990, *A&ASS*, **82**, 497

García-Lario, P., Manchado, A., Riera, A. et al.: 1991, *A&A*, **249**, 223

Hrivnak, B.J., Kwok, S., Volk, K.M.: 1989, *ApJ*, **346**, 265

Likkel, L., Omont, A., Morris, M., Forveille, T.: 1987, *A&A*, **173**, L11

Likkel, L., Forveille, T., Omont, A., Morris, M.: 1991, *A&A*, **246**, 153

Luck, R.E., Bond, H.E.: 1989, *ApJ*, **342**, 476

Manchado, A., Pottasch, S.R., García-Lario, P. et al.: 1989, *A&A*, **214**, 139

Montesinos, B., Cassatella, A., González-Riestra, R. et al.: 1990, *ApJ*, **363**, 245

Parthasarathy, M.: 1989, in *Evolution of peculiar Red Giant stars*, eds. H.R. Johnson and B. Zuckerman (Cambridge University Press), p. 384

Parthasarathy, M., Pottasch, S.R.: 1986, *A&A*, **154**, L16

Parthasarathy, M., García-Lario, P., Pottasch, S.R.: 1993, (in preparation)

Phillips, J.P., Riera, A., Mampaso, A.: 1990, *A&A*, **234**, 454 718

Stickland, D.J., Harmer, D.L.: 1978, *A&A*, **70**, L53

Trams N.R., van der Veen, W.E.C.J., Waelkens, C. et al.: 1990, *A&A*, **233**, 153

te Lintel Hekkert, P., Chapman, J.M., Zijlstra, A.A.: 1992, *ApJ*, **390**, L23.

van der Veen, W.E.C.J., Habing, H.J.: 1990, *A&A*, **231**, 404

Volk, K., Kwok, S.: 1989, *ApJ*, **342**, 345