THE ASTROPHYSICAL JOURNAL, 371:631–635, 1991 April 20

THE CARBON-RICH PROTO–PLANETARY NEBULA IRAS 22272+5435

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Received 1990 August 20; accepted 1990 October 2

ABSTRACT

Ground-based photometry and spectroscopy is presented for IRAS 22272+5435, a 9th mag star with a large infrared excess. The flux distribution is "double-peaked," with a visible and near-infrared component due to the reddened photosphere and a far-infrared component presumably due to a detached dust shell. About equal amounts of energy are detected from each. The spectrum is that of a peculiar G supergiant, Gp Ia. In addition, strong molecular bands of C_3 and C_2 are observed. The flux distribution is modeled and, together with published molecular-line radio observations, allows the determination of basic parameters of the central star and the dust shell. The source has the characteristics one would expect of a proto–planetary nebula, an object in transition from the asymptotic giant branch to the planetary nebula phase.

Subject headings: infrared: sources — nebulae: individual (IRAS 22272+5435) — nebulae: planetary — stars: circumstellar shells

1. INTRODUCTION

While asymptotic giant branch (AGB) stars are now widely accepted as progenitors of planetary nebulae, stars in the evolutionary stage between the AGB and planetary nebulae have remained undetected until recently. Primarily as a result of the *IRAS* sky survey, a number of candidates for post–AGB stars or proto–planetary nebulae (PPN) objects have been identified (Bidelman 1985; Lamers et al. 1986; Parthasarathy & Pottasch 1986; Pottasch & Parthasarathy 1988; Hrivnak, Kwok, & Volk 1988, 1989; van der Veen, Habing, & Geballe 1989). A common characteristic of these candidates is that they possess large far-infrared excesses above the photospheric continua of their A–G spectral-type central stars. The occurrence of a bright optical counterpart and a large far-infrared excess permits these objects to be studied at a variety of wavelengths. In the present study, we present optical and near-infrared photometry and optical spectroscopy of IRAS 22272+5435 and fit its flux distribution by a PPN model with a detached dust shell. The optical spectra display prominent molecular carbon features indicating a carbon-rich circumstellar envelope, which is in accord with its proposed post–AGB status.

2. OPTICAL IDENTIFICATION

The initial association of IRAS 22272+5435 with SAO 34504 (BD +54°2787, HDE 235858) was based upon the close positional agreement (<3″). We have confirmed this association by observing the source at 10 μm at NASA's Infrared Telescope Facility on 1988 July 27, using a bolometer with a 6″ aperture. Although standardized measurements were not made due to nonphotometric conditions, the strength of the signal from the optical object left no doubt that it was the strong source detected by *IRAS*.

The object appears pointlike on the Palomar Observatory Sky Survey prints, with no suggestion of nebulosity. A CCD image obtained by H. C. Harris (see below) with seeing of 2″–3″ also gives no indication of an extended object.

3. PHOTOMETRY

Optical photometry of IRAS 22272+5435 was obtained in 1989 August with the University of Hawaii (UH) 0.6 m telescope on Mauna Kea, Hawaii. A single-channel photometer was used with a GaAs detector and an aperture of 30″, and the measurements were transformed to the standard *UBV* and *RI* systems of Johnson and Cousins, respectively. Observations were also kindly made by H. C. Harris with the 1.0 m telescope of the US Naval Observatory (USNO) at Flagstaff, Arizona. These observations were made with a CCD, and transformed to closely match the standard BVI_c system. These are listed in Table 1. Both nights were of photometric quality and suitable for all-sky photometry, and stars from the list of Landolt (1983) were observed to standardize the measurements. No local comparison stars close to the object were observed. The optical photometry clearly shows the object to be variable, with a difference in V of 0.84 mag based on two observations. The colors of the object appear very red, with $(B-V) = 1.9$.

TABLE 1

NEW GROUND-BASED PHOTOMETRY OF IRAS 22272+5435

A. Visible

Date	U	B	V	R_c	I_c	Observatory
1988 Oct 18	...	10.68	8.68	...	6.72	USNO
1989 Aug 24	13.61	11.40	9.52	8.47	7.34	UH

B. Near-Infrared

Date	J	H	K	L	M	Observatory
1987 Oct 7	5.49	4.96	4.95	4.43	4.12	KPNO

NOTE.—Observational uncertainties (in mag) are as follows—visible: 0.02 (B through I_c) and 0.07 (U) at UH, 0.03 (B), 0.04 (V), 0.02 (I_c) at USNO; near-infrared: <0.03 (J through L) and 0.05 (M).

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Near-infrared *JHKLM* observations were obtained by R. Joyce with the 1.3 m telescope at Kitt Peak National Observatory (KPNO). The observations were made with an Insb detector, an aperture of 15″, and a N–S throw of 40″. These are also listed in Table 1.

4. OPTICAL SPECTROSCOPY

Ground-based, optical spectroscopy of IRAS 22272+5435 was carried out at the Dominion Astrophysical Observatory (DAO) on several nights in 1987, 1988, and 1989. Spectra were obtained with the 1.8 and 1.2 m telescopes using either an intensified reticon or a CCD detector.

The spectra of IRAS 22272+5435 were classified by comparison with a few spectral standards observed with the same instrumental setup and by comparison with the photographic spectral atlas of Keenan & McNeil (1976). The spectrum in general appears to be of G spectral type, and the strength of the Sr II 4077 line immediately suggests a supergiant luminosity. In Figure 1 we display a spectrum of 22272+5435, along with spectra of several supergiant stars: BS 8313 (9 Peg; G5 Ib), HD 6474 (G4 0–Ia), and BS 8752 (G5–K0 0–Ia). These spectra were obtained with a CCD and have a resolution of 3.0 Å. They are not flux-calibrated and include the instrumental response. The spectra were reduced using IRAF at the DAO.

Closer examination reveals some peculiarities which make it difficult to assign a unique spectral type to the star using the standard line-ratio criteria. The spectral class appears to be early G based upon the ratios of λ4172/λ4178 and Cr 4274/Fe 4271, but later than K0 based upon Cr 4254/Fe 4250, 4260. (In the latter two cases, we used higher resolution spectra of 22272+5435 and BS 8313 than those shown in Fig. 1.) The hydrogen lines appear to be too weak for an early-G spectral type, especially Hδ. The ratio Fe 4143/Hδ suggests G8 or later. Ca I 4226 appears relatively weak, with the suggestion that perhaps it is filled in with emission. Some of the difficulty in classification may arise from the additional anomalous lines presented in the spectrum of this star, as discussed below. Thus

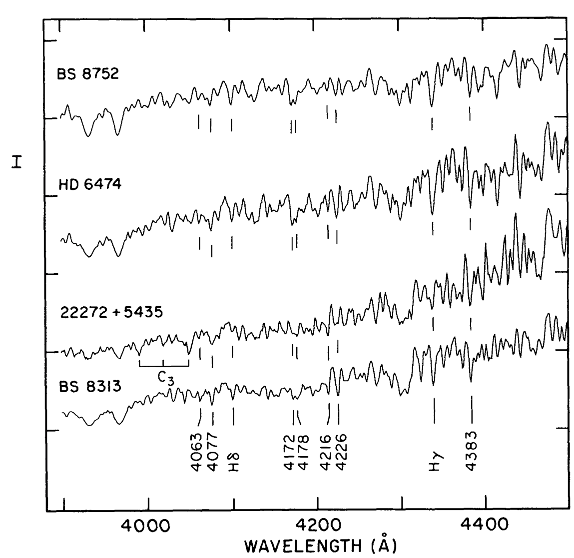

FIG. 1.—The spectrum of IRAS 22272+5435, compared with several G supergiants. Lines used in the classification are indicated. The spectra are displaced arbitrarily in intensity and are not flux-calibrated.

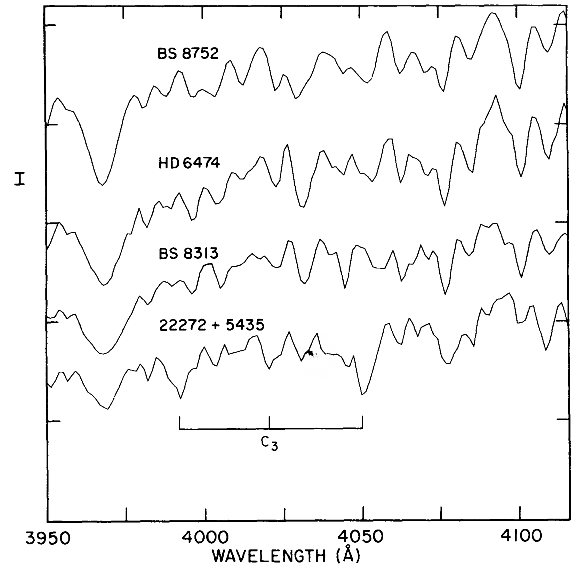

FIG. 2.—The spectrum of IRAS 22272+5435 in the region of the C_3 molecular features, compared with several G supergiants.

we cannot be more specific at present than to classify 22272+5435 as a peculiar G star.

The luminosity class of 22272+5435 was determined based upon the following ratios: Sr II 4077/Fe 4063, Y II 3983/Fe 4005, and Y II, Fe 4376/Fe 4383, all of which suggest 0–Ia; Fe, Ti II 4409/Fe 4404, and Y II, Fe 4442/λ4435, and the appearance of the G band, which suggest Iab. The relatively strong CN band head at λ4216 appears in 22272+5435, and thus the ratio λ4216/Ca 4226 could not be used because of its sensitivity to abundance differences; also the Ca I 4226 line appears weak with even the suggestion of emission. Additional spectra also show Ba II 4554 to be much stronger in 22272+5435 than in BS 8313 (G5 Ib; see Fig. 3). The strength of the *s*-process elements Sr, Y, and Ba in 22272+5435 might also be an indication of an abundance effect in addition to a luminosity effect. We conclude that Ia is the best classification. We note that this Gp Ia classification is the same as that assigned by Bidelman (1990) to his spectra of this source (see § 5).

A number of additional spectral features are seen in IRAS 22272+5435 which are not seen in any of the abovementioned stars. We have identified some of these as molecular carbon absorption. In particular, very strong features at λ4050, 3992, and possibly 4020 are attributed to C_3. These are displayed on an expanded scale in Figure 2. The continuum appears to be depressed shortward of about 4100 Å. These C_3 features have been seen in emission in comets and in absorption in late N-type carbon stars (McKeller 1948; Swings, McKeller, & Rao 1953). They have also been reported in one other PPN candidate, CRL 2688, the Egg nebula (Crampton, Cowley, & Humphreys 1975; spectral type F5 Ia). The observed wavelengths, corrected for the stellar radial velocity of -40 km s^{-1}, are listed in Table 2, together with the laboratory wavelengths. Because of the difficulty in placing the continuum in this late-type spectrum, equivalent widths were not measured for these features. The line at λ3992 appears to be asymmetric or blended, and the feature at 4020 is very blended. The strong features at λ4050 and 3992 are both observed at wavelengths redward of the laboratory wavelengths, by an average of $+1.3$ Å. A redward shift of $+0.8$ Å in these two lines was found by

TABLE 2

MOLECULAR CARBON FEATURES IN THE SPECTRUM OF IRAS 22272+5435

λ_0 (Å)	λ_{lab} (Å)	$\Delta\lambda$ (Å)	Molecule
3992.44	3990.8	+1.6	C_3
4021.2	4018.3	+2.9	C_3:
4050.75	4049.8	+1.0	C_3
4714.64	4715.2	−0.6	C_2
4735.98	4737.1	−1.1	C_2
4742.36	4744	−2	C_2:
4749.09	4752	−3	C_2:

Crampton et al. (1975) in CRL 2688, and Swings et al. (1953) found a redward shift of +2.5 Å in the spectrum of the four carbon stars which they studied. The general agreement between the observed and laboratory wavelengths leads us to conclude that the C_3 molecule is the source of these very strong lines.

Molecular absorption by C_2 is also seen in spectra of 22272+5435 which extend farther to the red. The bands at λ4737 and 4715 are shown in Figure 3. The measured wavelengths for these lines are, however, approximately 1 Å shorter than the laboratory wavelengths and are listed in Table 2. Slightly longward of the red edge of the C_2 λ4737 feature one can distinguish two features which may correspond to the presence of the C^{13} isotope. These are at λ4744 ($C^{12}C^{13}$) and at λ4752 ($C^{13}C^{13}$). The strength of these lines would indicate a relatively high abundance of C^{13}. Another spectrum, extending to longer wavelengths, also shows the strong C_2 feature at λ5165.

There are additional weaker lines seen in the spectrum of IRAS 22272+5435 which are not seen in the three stars with which we have compared it. Identification of these peculiar lines will require further observations at higher resolution.

A spectrum taken in the region of Hα shows no Hα emission.

5. VARIABILITY

IRAS 22272+5435 has been previously recognized to vary in light and is assigned the variable star name V354 Lac

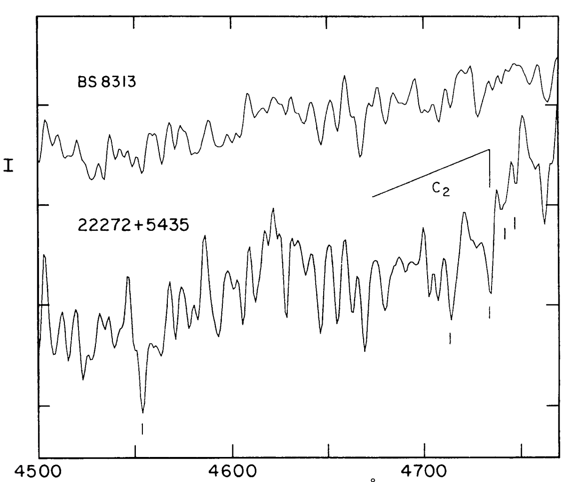

FIG. 3.—The spectrum of IRAS 22272+5435, showing C_2 absorption features at λ4737 and 4715 and also the features at λ4744 and 4752 suggested to be due to the C^{13} isotope. A spectrum of BS 8313 is included for comparison. The strong Ba II 4554 line is also indicated.

(previously designated as BV 319 and 319 Lac). The nature of its variability, however, is not yet established. Filatov (1961) calls it an irregular variable with a variation of 1.5–2.0 mag, while Strohmeier & Knigge (1960) list it as a possible short-period variable with an amplitude of 0.5 mag. (Note that while Strohmeier & Knigge [1960] identify the variable by its BD number, the position which they list is 2′ north of the BD and SAO position for the same epoch; however, there is no other star closer of the appropriate brightness and so they have presumably made an error in the listing of its position.) Our new observations reveal a variation in V of 0.8 mag based upon only two observations. A new effort to monitor the system photometrically is clearly warranted. A comparison of our near-infrared observations with those of van der Veen et al. (1989) obtained one year earlier and those of Manchado et al. (1989) indicates a variability of 0.2 mag in the near-infrared. The variability index assigned to the *IRAS* data is 3%, indicating little variability in the mid-infrared over a 6 month interval.

We investigated the history of the spectral classification of this object to see if it may have varied. A recent spectral classification of the system is Gp Ia, based upon an objective prism plate taken in 1987 (Bidelman 1990, private communication). Several earlier low-dispersion spectral classifications of IRAS 22272+5435 have been published. The object is classified as K5 in the HD catalog (HDE 235858). It appears as DO 41457 in the Dearborn Observatory catalog (Lee, Gore, & Bartlett 1947), where it was independently classified as K5. McCuskey (1955) classified it as M0 III: from spectra with a dispersion of 283 Å mm^{-1} at Hγ. It is by far the reddest star among the more than 4000 stars in his study, and the only one among the dozen M0 III stars in which the classification was indicated as uncertain. Perhaps this late and uncertain classification was influenced by the redness of the star, which we now know to be due in large part to the circumstellar dust, and the molecular features. It is hard to know without examining these older spectra if the spectral type of the system has changed and become earlier over the past 40 yr, or if the classifiers were simply misled by the redness of the star and the unusual molecular features. Bidelman (1990, private communication) comments that he has examined older spectra of this object, and that these do not differ from the Gp Ia spectrum cited above; therefore observed change in the spectrum appears unlikely. If the change were real, it would, however, be consistent with the expected direction of spectral change as the star evolves toward higher temperatures.

A search for radial velocity variability is presently underway using the high-precision radial velocity spectrometer on the DAO 1.2 m telescope. An initial observation kindly made by R. D. McClure indicated a radial velocity of -39.6 ± 0.8 km s^{-1}.

6. CARBON-RICH CIRCUMSTELLAR ENVELOPE

If this *IRAS* source is a PPN, then the remnant of its circumstellar envelope should be detectable in radio molecular line emission as well as in the far-infrared continuum radiation (Kwok 1982). A number of molecular lines have been detected in emission from IRAS 22272+5435. Zuckerman, Dyck, & Claussen (1986) detected CO (J = 1–0) emission with a local standard of rest velocity of V(LSR) = −30.9 km s^{-1} and an expansion velocity of V_e = 11.6 km s^{-1}. Lindqvist et al. (1988) also measured CO (J = 1–0), with V(LSR) = −28.3 km s^{-1} and V_e = 10.5 km s^{-1}. In addition, they also measured HCN (J = 1–0) with V(LSR) = −24.5 km s^{-1} and V_e = 13.3 km s^{-1}

and detected CS emission. Woodsworth, Kwok, & Chan (1990) recently measured CO ($J = 2$–1) with V(LRS) $= -28.0$ km s^{-1} and $V_e = 9.6$ km s^{-1}. Searches for SiO ($v = 1$, $J = 2$–1) and OH (1612 MHz) by Lindqvist et al. (1988) and H_2O by Zuckerman & Lo (1987) yielded no detections and only upper limits. The presence of carbon molecules and absence of oxygen molecules indicates that the object is carbon-rich. (Note that the optical absorption-line radial velocity listed in § 5 transforms to -33 km s^{-1} in the LSR frame; this is slightly more negative than the molecular line measurements.)

The detection of these several carbon molecules in the circumstellar envelope of IRAS 22272+5435 strengthens the similarity between it and the circumstellar envelope of CRL 2688, a PPN candidate, and IRC +10216, an infrared carbon star, in which CO, CS, CN, and many long-carbon chain molecules have been observed (Olofsson 1987). Thus the radio and optical data both indicate that the object is extremely carbon-rich. Kwok, Volk, & Hrivnak (1989) attribute the recently discovered 21 μm emission feature seen in IRAS 22272+5435 and three other PPN candicates to carbon-bearing grains in the circumstellar envelopes of these objects.

7. MODELING OF THE FLUX

A comparison of the visual and infrared measurements for the source indicates a double-peaked flux distribution, with a large far-infrared excess above the photospheric continuum. This is displayed in Figure 4, where we have plotted our visual and near-infrared photometry together with the photometry and LRS spectroscopy of *IRAS*. Flux calibration factors for the visible photometry were taken from Bessell (1979) and for the near-infrared were provided by R. Joyce. The visual and near-infrared flux is arising from the reddened photosphere of the star and the far-infrared presumably from the cool dust shell. An estimate of the interstellar extinction was derived from the work of Neckel & Klare (1980), and yields $A_V = 1.3$ mag. We used this together with the average extinction law of Cardelli, Clayton, & Mathis (1989) to correct the observed visual and near-infrared observations for the effect of interstellar extinction. Approximately equal amounts of energy, 2.3×10^{-8} and 3.5×10^{-8} ergs cm^{-2} s^{-1}, are received from the photosphere and the dust shell, respectively, with the former amount increasing to 3.4×10^{-8} when corrected for interstellar extinction. We note that Pottasch & Parthasarathy (1988) have previously derived some of the infrared properties of this source based primary on the *IRAS* data.

We have previously modeled the flux distribution for this object, although without the inclusion of this recent optical photometry, using a dust radiative transfer code (Kwok et al. 1989). The model fit is shown as a dashed line in Figure 4. The wide separation of the photospheric and circumstellar components in the energy distribution suggests that the dust envelope is detached from the photosphere, and the inner radius of the dust envelope can be determined by the model fitting. The model is in general agreement with the observations, apart from the unusual 21 μm feature and slightly high values in the visual. The fit in the visual region could be improved by increasing the extinction by 0.5 mag above the estimated interstellar extinction of $A_v = 1.3$ mag. Assuming the kinematic distance for the source of 2.7 kpc (Woodsworth et al. 1990), one can determine a total luminosity of $L = 2.8 \times 10^4$ $L_\odot$, an inner shell radius of 1.3×10^{16} cm (880 AU), and an age

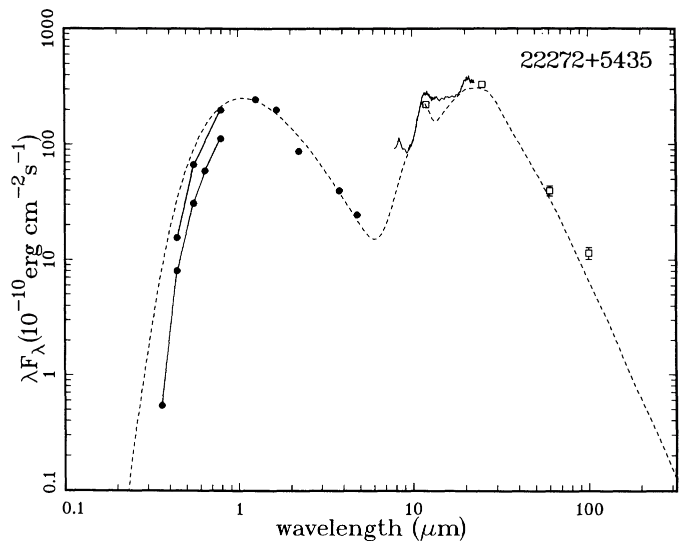

FIG. 4.—The observed flux distribution of IRAS 22272+5435, compared with the model results. Filled circles indicate our new ground-based photometry, open squares the *IRAS* photometry, and the solid line the *IRAS* LRS spectroscopy. Solid lines join the visible observations of the same night. Note the variability in the BVI_c photometric observations. The dashed line shows the model fit, as discussed in the text.

since the termination of mass loss of 400 yr (assuming uniform expansion of the dust with the gas).

8. DISCUSSION

IRAS 22272+5435 displays the characteristics expected of PPN–a double-peaked flux distribution indicative of a well-detached, cool shell, which is observed to be expanding around a very luminous central star. It is clearly carbon-rich, as evidenced by the detected C_2 and C_3 molecules and supported by the molecular-line observations. Such an enhancement of carbon is consistent with the expectation for a post–AGB star undergoing thermal pulses, which mix carbon to the surface (Iben & Renzini 1983).

Near-infrared spectroscopy of IRAS 22272+5435 revealed a weak CO absorption feature at 2.3 μm (van der Veen et al. 1989). Recently the C_3 molecule was detected in IRC +10216, where it was observed in high resolution in the 5 μm region (Hinkle, Keady, & Bernath 1988). A similar observation could be performed for this object. Further near-infrared and higher resolution optical spectroscopic studies of this PPN would be expected to yield additional insights into the chemistry of this important transitional object.

We thank H. C. Harris and R. Joyce for making some of the observations presented here, M. Bolte for help in reducing the CCD spectra, and K. Cudworth for acquiring some of the references. Phil Langill also helped in reducing some of the spectra and in obtaining the visual photometry. B. J. H. acknowledges the support of the National Space Science Data Center in providing access to the SIMBAD data base. This research was supported by grants to B. J. H. from NASA administered by the American Astronomical Society and under NASA's Astrophysical Data Program, and to S. K. from the Natural Sciences and Engineering Research Council of Canada.

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