AN ABUNDANCE ANALYSIS OF THE NEW CARBON-RICH PROTO–PLANETARY NEBULA IRAS 06530−0213

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ABSTRACT

In this paper we present a study of the proto–planetary nebula (PPN) IRAS 06530−0213 based on low- and high-resolution spectra. The low-resolution spectrum shows that the star is an F5 supergiant with molecular C2 and C3 and enhanced s-process lines. From the high-resolution spectra, the following atmospheric parameters were determined: $T_{\text{eff}} = 6900$ K, $\log g = 1.0$, and $\xi = 4.5$. Abundance analysis shows that IRAS 06530−0213 is metal-poor ([Fe/H] = −0.9) and overabundant in carbon ([C/Fe] = 1.3), nitrogen ([N/Fe] = 1.0), and s-process elements ([s-process/Fe] = 1.9), indicating asymptotic giant branch (AGB) nucleosynthesis and deep convective mixing. From the analysis of circumstellar C2 and CN molecular bands in the spectrum of IRAS 06530−0213, an envelope expansion velocity of $V_{\text{exp}} = 14 \pm 1$ km s$^{-1}$ was determined, a typical value for post-AGB stars. Also typical of PPNs is the double-peaked spectral energy distribution. The properties of both the photosphere and circumstellar envelope suggest that IRAS 06530−0213 is unambiguously a low-mass, carbon-rich PPN. For comparison purposes, new, high-resolution spectra of the well-known PPN HD 56126 (IRAS 07134+1005) were also analyzed and compared with previous results.

Subject headings: circumstellar matter — stars; abundances — stars: AGB and post-AGB — stars: individual (HD 56126, IRAS 06530−0213)

1. INTRODUCTION

Proto–planetary nebulae (PPNs) represent an important transitional phase in the evolution of low- and intermediate-mass stars, between the asymptotic giant branch (AGB) and the planetary nebula (PN) phases. During this phase, the circumstellar envelope (CSE) of gas and dust is detached and expanding away from the star. The star, meanwhile, is increasing in surface temperature as it moves approximately horizontally (constant luminosity) across the H-R diagram. This evolutionary phase is expected to last several thousand years, depending on the mass of the star (Bögli 1995). When the temperature of the star becomes high enough to significantly photoionize the gas ($T_s > 30,000$ K), an emission-line spectrum is seen and the star has passed to the PN phase. However, when still in the PPN phase, the nebula is small and seen only in reflected light.

The study of PPNs has grown over the past two decades, following the identification of PPN candidates based on their infrared excesses in the IRAS database. (The infrared emission arises from the absorption and reemission of radiation from their circumstellar dust.) The PPN/post-AGB nature of these stars is supported by several lines of evidence. These include the following: (1) the spectral energy distribution (SED), based on the visible, near-infrared, and mid-infrared flux measurements, reveals a double-peaked SED with approximately equal amounts of flux received from the reddened photosphere and the warm dust ($T_d \sim 150–250$ K); (2) millimeter spectral line observations (CO or OH) reveal an expanding gas envelope with $V_{\text{exp}} \sim 10$ km s$^{-1}$; (3) low-resolution spectra show the expected spectral and luminosity class (B–G supergiants); (4) high-resolution spectra show the expected evidence of nucleosynthesis during the AGB phase of evolution. A description of the discovery and basic properties of PPNs is given by Kwok (1993), with recent updates from higher resolution studies discussed by Kwok (2000, pp. 151–166) and Hrivnak (2003).

The discovery of molecular carbon, C2 and C3, in the blue region of the visible spectrum (Hrivnak 1995) and C2 and CN in the red region (Bakker et al. 1996) of several PPNs indicated that they were carbon-rich. Interestingly, these same carbon-rich PPNs also have been found to display an unidentified feature in their mid-infrared spectra, the so-called 21 $\mu$m feature (Kwok, Volk, & Hrivnak 1989, 1999).

Quantitative abundance studies of the these PPNs with molecular carbon have determined that they are somewhat metal-poor, with an overabundance of CNO and a large overabundance of the s-process elements such as Y, Zr, La, Ce, and Nd (Van Winckel & Reyniers 2000; Reddy et al. 2002). These studies provide strong evidence that these objects are post-AGB stars that have undergone nucleosynthesis and convective mixing during the AGB phase.

In this paper we report on our study of the new carbon-rich PPN, IRAS 06530−0213. Its likely identification as a PPN was reported by Hu et al. (1993), who classified it as FOI with $V = 14$. Our photometry and low-resolution spectroscopy confirm the basic results of Hu et al. (1993) as to its PPN nature, but they also reveal for the first time the presence of C2 and C3. New high-resolution spectra were obtained to determine detailed abundances of the elements and confirm the post-AGB nature of the star. On the basis
of its SED, spectral classification, elemental abundances, and CSE, IRAS 06530–0213 is shown unambiguously to be a low-mass PPN. Also included is the analysis of new high-resolution spectra of the relatively well-known, bright \((V = 8.2)\) PPN HD 56126 (IRAS 07134+1005; F5 I). Although it has been the subject of previous abundance analyses, we have included it for the purpose of comparison with the results of IRAS 06530–0213. Preliminary results of this study have been presented by Reddy & Hrivnak (1999).

2. OBSERVATIONS

2.1. Visible and Infrared Photometry

We had initially selected IRAS 06530–0213 as a PPN candidate based on its IRAS colors, which peaked in the 25 \(\mu m\) bandpass. Correlation with the STScI Guide Star Catalog revealed a 14th magnitude star close to the IRAS position. The association with the IRAS source was confirmed by a ground-based 10 \(\mu m\) observation carried out on the United Kingdom Infrared Telescope on Mauna Kea under their Service Observing program. A measurement of \(N = 2.32 \pm 0.04\) was made on 1993 May 6.

Standardized photometry of IRAS 06530–0213 was carried out at Kitt Peak National Observatory (KPNO). Visible light observations were made using a CCD on the 0.9 m telescope on 1995 September 11, and near-infrared observations were made using the Simultaneous Quad Infrared Imaging Device (SQIID) on the 1.3 m telescope on 1993 November 9 and 10. SQIID used a dichroic crystal to separate the incoming beam so that it could be observed in four infrared bandpasses simultaneously. The resulting photometric values are listed in Table 1. They are in good agreement with the previously published photometric values of Hu et al. (1993), Reddy & Parthasarathy (1996), and Garcia-Lario et al. (1997). The object appears very red, with \((B-V) = 2.3\).

2.2. Low-Resolution Spectroscopy

A low-resolution spectrum of IRAS 06530–0213 was obtained on 1992 October 9 with the Gold Camera Cassegrain Spectrograph on the 2.1 m telescope at KPNO. The spectrum had a wavelength range of 3850–7600 \(\AA\) and a resolution of 8.0 \(\AA\). The spectrum was reduced with IRAF\(^2\) using standard reduction procedures: bias subtraction, flat-field correction, sky subtraction, one-dimensional extraction, and wavelength calibration using an arc lamp (He-Ne-Ar). Several spectral standards were also observed.

2.3. High-Resolution Spectroscopy

High-resolution spectra of IRAS 06530–0213 were obtained with the 2.7 m telescope at McDonald Observatory on 1997 October 17 \((R \approx 55,000)\) and 2001 December 10 \((R \approx 45,000)\). The telescope was equipped with a cross-dispersed coude echelle spectrograph (Tull et al. 1995) and a CCD \((2048 \times 2048\) pixels).

Three individual spectra of 45 minutes each were acquired on each night, and the spectra on each night were combined to remove cosmic-ray hits and to improve the signal-to-noise ratio \((S/N)\). For the purpose of wavelength calibration, Th-Ar comparison spectra were acquired before and after each of the sets of program star exposures.

IRAS 06530–0213 is faint \((V = 14.1)\) and highly reddened. Because of this, only a moderate \(S/N\) of 30 at 6560 \(\AA\) was achieved on the earlier date and a higher \(S/N\) of 80 at 6560 \(\AA\) at slightly lower resolution was achieved on the later date. We could confidently only use the spectra in the region between 5200 and 9200 \(\AA\) but not at shorter wavelengths where the signal decreases rapidly. A hot, rapidly rotating bright star was also observed for use in distinguishing telluric lines from the stellar features.

High-resolution spectra of HD 56126 were observed on 1996 December 23 \((t_{\text{exp}} = 30\) minutes, \(R \approx 55,000\)\) and 2002 November 14 (two spectra of \(t_{\text{exp}} = 30\) minutes, \(R \approx 55,000\) with the same telescope and equipment. The observations cover the wavelength range 4000–9800 \(\AA\) with gaps between echelle orders, and they result in spectra with \(S/N\) ranging from 100 to 400.

These high-resolution spectra were reduced using IRAF. Standard reduction procedures were employed, which consisted of bias subtraction, flat-field image correction, extraction of one-dimensional spectra, wavelength calibration, and continuum fitting.

3. LOW-RESOLUTION SPECTRUM: CLASSIFICATION

The extracted blue part \((3800–5000\ \AA)\) of the low-resolution spectrum of IRAS 06530–0213 is displayed in Figure 1, along with the spectra of two supergiants shown for comparison. The \(\gamma\)-axis is plotted on a logarithmic scale to display the weaker features in the blue more clearly. A few prominent spectral features are identified in the figure. Of particular importance is the identification of strong molecular \(C_2 (\lambda 4737)\) and \(C_3 (\lambda 3991, 4050)\) features. Also seen is a strong Ba \(\Pi\) feature at 4554 \(\AA\). These enhanced molecular and \(s\)-process features are commonly seen in carbon-rich PPNs (Hrivnak 1995).

The weak CH band at 4300 \(\AA\) \((G\) band\) suggests that the spectral type is earlier than \(G0\), and the ratio of the strengths of the \(Ca\ \Pi\ H\) line and the \(Ca\ \Pi\ K + H\alpha\) lines \((\sim 1.0)\) indicates that it is not earlier than \(F0\). From comparison with spectral standards, we assign the spectral classification F5 I. As seen in Figure 1, the Balmer profiles \((H\beta, H\gamma, \text{ and } H\delta)\) and metallic lines, such as Fe at 4045 \(\AA\) and \(Ca\ \Pi\ H\) and \(K\), are weaker than expected in a star of spectral class between F5 and G2. This may be due to some emission infilling of the Balmer profiles and to a low abundance of metals. Hu et al. (1993) and Reddy & Parthasarathy (1996) had classified the object F0 I, but that appears to be somewhat too early a

### Table 1

| Observation Date | Bandpass | Value |
|-----------------|----------|-------|
| 1995 Sep 11     | \(B\)    | 16.40 ± 0.03 |
|                 | \(V\)    | 14.06 ± 0.04 |
|                 | \(R\)    | 12.69 ± 0.04 |
|                 | \(I\)    | 11.44 ± 0.02 |
| 1993 Nov 9, 10  | \(J\)    | 9.46 ± 0.02  |
|                 | \(H\)    | 8.87 ± 0.02  |
|                 | \(K\)    | 8.43 ± 0.02  |
|                 | \(L\)    | 8.0 ± 0.3    |

\(^2\)IRAF is distributed by the National Optical Astronomical Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.
spectral type for our spectrum. From the analysis of the low-resolution spectrum, we qualitatively describe IRAS 06530−0213 as a metal-poor, F5 supergiant with enhanced carbon and s-process elements. These characteristics suggest that it is indeed a post-AGB star, consistent with the assignment as a PPN.

4. ANALYSIS OF HIGH-RESOLUTION SPECTRUM

4.1. Description of Spectrum

The high-resolution spectrum of IRAS 06530−0213 resembles that of HD 56126. They both possess sharp spectral features and weak metallic lines, suggesting that IRAS 06530−0213 is also an evolved, metal-poor star. In Figure 2 are displayed continuum-fitted, normalized regions of the spectra of both the stars, showing the presence of strong carbon lines and strong lines of s-process elements. The spectra of both stars exhibit strong and complex profiles of Hα, Na D, and K λ, with Hα displaying emission components in both stars. Absorption bands of C2 Phillips and CN Red system are also present in both; these are displayed and discussed in detail later in this study. The C2 Swan band at 5165 Å is also seen in HD 56126.

4.2. Spectral Line Analysis

Atomic line identification was done using the solar spectrum (Moore, Minnaert, & Houtgast 1966). In the spectra, 99 lines were identified for IRAS 06530−0213 and 207 lines were identified for HD 56126 for which the equivalent widths could be measured confidently and which also have reliable atomic parameters. The reason for the fewer lines measured for IRAS 06530−0213 is the significantly lower S/N of the spectrum, especially at the shorter wavelengths, as a result of its relative faintness. A large number of neutral carbon lines (19 for IRAS 06530−0213 and 33 for HD 56126) were measured. Very few metallic lines are seen in the spectra, which is presumably due to both the mid-F spectral types and also a real deficiency in metals (see § 4.4). We tried to measure as many lines as possible that were common to both spectra. However, this was restricted by the difference in their spectral quality and also by the gaps in the spectra.

Radial velocities were measured using many lines of C i, O i, N i, Fe i, and Fe ii. This resulted in heliocentric velocities for IRAS 06530−0213 of $V_r = 51.0 \pm 1.0$ (1997 October 17) and $50.4 \pm 1.0$ km s$^{-1}$ (2001 December 10). The radial velocities measured for IRAS 06530−0213 from photospheric atomic lines are in good agreement with the values measured from millimeter CO measurements, $V_r = 50$ km s$^{-1}$ ($V_{LSR} = 33$ km s$^{-1}$; Hu et al. 1994).

From the two spectra of HD 56126, we measured $V_r = 83.3 \pm 0.5$ (1996 December 23) and $86.2 \pm 0.5$ km s$^{-1}$ (2002 November 14). HD 56126 is known to undergo photospheric pulsations with radial velocities of 81.7–91.8 km s$^{-1}$ (Lèbre et al. 1996). Our measured values of $V_r$ fall in this range.

Equivalent widths ($W_r$) were measured by fitting Gaussian profiles to the observed lines. Measurements were made of 15 elements (C, N, O, Mg, Si, Ca, Ti, Fe, Y, Zr, Ba, La, Ce, Pr, and Nd) for IRAS 06530−0213 and of 19 elements (C, N, O, Mg, Si, S, Ca, Sc, Ti, Cr, Fe, Y, Zr, Ba, La, Ce, Nd, Sm, and Eu) for HD 56126.

Oscillator strengths ($gf$-values) were taken from various sources. For Fe i and Fe ii transitions, the $gf$-values critically reviewed by Lambert et al. (1996) were adopted, and for C, N, and O, the $gf$-values were taken from compilations by Wiese, Fuhr, & Deters (1996). For the rest of the lines used in this study, $gf$-values were taken from compilations of either the NIST$^3$ or the VALD$^4$ database.

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$^3$ See the Web site at http://physics.nist.gov/cgi-bin/AtData.
$^4$ See the Web site at http://www.astro.univie.ac.at.
4.3. Atmospheric Parameters

The model atmospheric parameters of effective temperature \(T_{\text{eff}}\) and surface gravity (\(\log g\)) can in principle be estimated from photometry and from spectral classification. However, in practice these two methods have often proven ineffective in the case of evolved post-AGB stars. In many cases these stars are highly reddened, and it is not possible to determine the precise contributions of the interstellar and circumstellar components to derive the intrinsic stellar colors. Spectral classification also may lead to erroneous temperatures due to the metal-weak nature of the stars and the difficulty in determining the continuum in the blue part of the spectrum in the presence of strong molecular features. Inspection of Figure 1 shows that the Balmer profiles of IRAS 06530—0213 are weak for its assigned F5 I spectral class. It is not clear whether this weakness is due to emission filling (H\(\alpha\) shows emission) or to a real deficiency in hydrogen content. If the stars are H-poor, then the standard model analysis may not be applicable. In fact, there are stars (e.g., R CrB type) that are thought to be in a post-AGB evolutionary phase but with severely H-depleted (or He-rich) atmospheres (see Pandey et al. 2001). These stars presumably evolved from main-sequence stars with normal H content. Thus, it is possible that IRAS 06530—0213 is in fact mildly H-poor, but in the absence of He lines (expected to be seen only at higher temperatures) we cannot determine this. In the case of these two stars, their spectral classes were only used to estimate initial values for the temperature and gravity.

The atmospheric parameters \(T_{\text{eff}}\) and \(\log g\) were first derived using a \(T_{\text{eff}}-\log g\) analysis. In this method, we computed abundances for neutral and singly ionized species of Fe and Ca for different values of \(T_{\text{eff}}\) and \(\log g\). A value for the microturbulent velocity of \(\xi_t = 5\) km s\(^{-1}\) was assumed, which is a typical value for evolved supergiants. In Figure 3 are plotted curves of equal abundances of Fe \(i\) and Fe \(ii\) and of Ca \(i\) and Ca \(ii\) for each star. The location of the intersection of the two curves yields the values of \(T_{\text{eff}}\) and \(\log g\) and also the abundances of Fe and Ca for each star. From this analysis we find \(T_{\text{eff}} = 6700\) K and \(\log g = 1.3\) for IRAS 06530—0213 and \(T_{\text{eff}} = 6850\) K and \(\log g = 0.2\) for HD 56126.

In this analysis, only lines were used that were of similar strength (75–90 mA for IRAS 06530—0213 and 30–40 mA for HD 56126) for all species. In this way the influence of \(\xi_t\) was minimized, since all of the lines respond in almost the same way to changes in \(\xi_t\). To confirm this, computations were performed with \(\xi_t = 3\) and 7 km s\(^{-1}\), and it was found that these resulted in little or no difference in the values of the intersections, although the values of the abundances were obviously changed, by \(\pm 0.1\) to \(\pm 0.2\) dex. The advantage of this method is that one can derive three parameters, \(T_{\text{eff}}, \log g,\) and metallicity, simultaneously. However, to determine more accurate values of these parameters, one should use neutral and ionized species of many elements, rather than only two as we were able to do.

As a second approach to determining the atmospheric parameters, we used the standard procedure of analyzing the excitation and ionization equilibria of Fe and C \(\text{i}\) lines. The value of \(T_{\text{eff}}\) was determined by examining the effect of different \(T_{\text{eff}}\) values on the derived Fe \(i\) abundances, to find the value for which the abundances of Fe \(i\) are independent of the lower excitation potentials (LEPs) of individual Fe \(i\) lines. To minimize the effect of \(\xi_t\), weak (25–55 mA) Fe \(i\) lines were used. The value of \(\log g\) was determined using the ionization balance of neutral and singly ionized lines of Fe. The value of \(\xi_t\) was determined by comparing abundance versus reduced equivalent width (\(W_{\lambda}\)) for many Fe \(i\) and C \(\text{i}\) lines with a wide range of \(W_{\lambda}\) (20–150 mA). From this, the value of \(\xi_t\) was determined for which the reduced equivalent widths of Fe and C were independent of the strength of their individual lines. These results are displayed graphically for IRAS 06530—0213 in Figure 4. After many iterations, the following atmospheric parameters were determined:

\[
T_{\text{eff}} = 6900 \pm 250\ \text{K}, \quad \log g = 1.0 \pm 0.5, \quad \xi_t = 4.5 \pm 0.5\ \text{km s}^{-1},
\]

and \([\text{M/H}] = -1.0\) for IRAS 06530—0213, and

\[
T_{\text{eff}} = 7250 \pm 250\ \text{K}, \quad \log g = 0.50 \pm 0.5, \quad \xi_t = 5.0 \pm 0.5\ \text{km s}^{-1},
\]

and \([\text{M/H}] = -1.0\) for HD 56126. The uncertainties listed are based on the sensitivities of the abundances to variations in these parameters.

In this study, the atmospheric parameters derived in three different ways: (1) low-resolution spectrum, (2) \(T_{\text{eff}}-\log g\) diagram, and (3) excitation and ionization equilibria, are found to be in good agreement. The derived atmospheric parameters for HD 56126 in this study are in very good agreement with those derived for this same star in previous studies (Klochkova 1995; Van Winckel & Reyniers 2000). The adopted model atmosphere parameters, based on our excitation ionization analysis, are listed in Table 2 and are used in the subsequent abundance analyses.

4.4. Abundances

In deriving the elemental abundances, the widely used plane-parallel, line-blanketed, local thermodynamic equilibrium (LTE) stellar model atmospheric grids of Kurucz were used, which are computed using the ATLAS9 code.3

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3 See the Kurucz Web site at http://kurucz.harvard.edu/grids.html.
Abundances were primarily computed through the fine analysis method, in which the theoretical strength of each line is computed and the model abundances are iterated until the computed line strengths are matched with the observed ones. The fine analysis was done using a modified version of the computer program MOOG (Sneden 1973). The results of this analysis are summarized in Table 3. In the table, n represents the number of lines measured, log \( \epsilon(X) \) is the logarithmic abundance of the particular element \( X \) with respect to a hydrogen abundance of \( \log \epsilon(H) = 12.0 \), and [X/H] and [X/Fe] are the logarithmic ratios with respect to hydrogen and iron, respectively, relative to the solar values. The solar values of Grevesse & Sauval (1998) have been used except for C and O, for which we have adopted more recently derived solar abundance estimates for our two stars may be even slightly higher, since we note these possible corrections to the abundances derived for C and N but

\[ [\text{O/Fe}] = 0.5 \text{ (IRAS 06530–0213) and [O/Fe]} = 0.7 \text{ (HD 56126) were derived. Thus, both stars are overabundant in } \text{O relative to Fe. Comparison of the computed spectrum with the observed spectrum in the region of } \text{O i triplet and in the region of the } \text{C lines at } 7115 \text{ Å is shown for IRAS 06530–0213 in Figure 5.} \]

Recent studies of C and N suggest that there are significant non-LTE effects in this temperature and low-gravity domain and in low-metallicity stars. The study of non-LTE effects on the neutral C lines in the atmospheres of F- and A-type dwarfs (Rentzsch-Holm 1996) suggests that non-LTE effects are significant even for dwarfs. Venk (1995) estimates a similar non-LTE correction for the F-type supergiant HR 6130. The non-LTE studies of N i lines by Luck & Lambert (1985) and Venn (1995) show that N i lines are significantly affected by non-LTE effects. However, the corrections for our two stars may be even slightly higher, since both HD 56126 and IRAS 06530–0213 are more metal-deficient than the stars considered in the above studies. Non-LTE effects become more significant in metal-poor stars as a result of overionization of neutral elements due to the stronger UV radiation field. These studies suggest non-LTE corrections of approximately −0.3 and −0.4 dex for the abundances of C and N, respectively. We note these possible corrections to the abundances derived for C and N but

![Fig. 4.—Spectroscopic determination of atmospheric parameters \( T_{\text{eff}}, \xi_t, \) and \( \log g \) for IRAS 06530–0213 using Fe i (crosses), Fe ii (filled circles), and C i lines (asterisks) for IRAS 06530–0213.](image1)

![Fig. 5.—Spectral synthesis of the wavelength regions 7115 and 6156 Å for IRAS 06530–0213. The spectra computed from the adopted model fit well with the observed spectra (points) for the abundances given in Table 3.](image2)

### Table 2

| Name               | \( T_{\text{eff}} \) (K) | \( \log g \) (cm s\(^{-2}\)) | \( \xi_t \) (km s\(^{-1}\)) | [M/H] | \( V_r \) (km s\(^{-1}\)) |
|--------------------|-------------------------|-------------------------------|-------------------------------|-------|--------------------------|
| IRAS 06530–0213    | 6900 ± 250              | 1.0 ± 0.5                     | 4.5 ± 0.5                     | −1.0  | 51.0 ± 1.0 (1997 Oct 17) |
|                    |                         |                               |                               |       | 50.4 ± 1.0 (2001 Dec 10)  |
| HD 56126           | 7250 ± 250              | 0.50 ± 0.5                    | 5.0 ± 0.5                     | −1.0  | 83.3 ± 0.5 (1996 Dec 13)  |
|                    |                         |                               |                               |       | 86.2 ± 0.5 (2002 Nov 14)  |
TABLE 3
SUMMARY OF ELEMENTAL ABUNDANCES

| Species | IRAS 06530–0213 | HD 56126 |
|---------|-----------------|----------|
|         | n | log$\epsilon$(X) | $\sigma$ | [X/H] | [X/Fe] | n | log$\epsilon$(X) | $\sigma$ | [X/H] | [X/Fe] |
| Cl      | 19 | 8.72$^a$ | 0.17 | 0.33$^a$ | 1.26$^a$ | 33 | 8.09$^a$ | 0.15 | $-0.30^a$ | 0.70$^a$ |
| N       | 6  | 7.97$^b$ | 0.28 | 0.05$^a$ | 0.08$^b$ | 7  | 8.01$^b$ | 0.12 | $-0.10^b$ | 0.90$^b$ |
| O       | 3  | 8.36 | 0.10 | $-0.39$ | 0.54 | 3  | 8.40 | 0.10 | $-0.29$ | 0.71 |
| Mg I    | 2  | 6.73 | 0.17 | $-0.85$ | 0.08 | 5  | 6.76 | 0.13 | $-0.82$ | 0.18 |
| Si I    | 5  | 6.90 | 0.11 | $-0.65$ | 0.27 | 3  | 6.78 | 0.11 | $-0.77$ | 0.23 |
| S       | ... | ... | ... | ... | ... | 2  | 6.49 | 0.10 | $-0.72$ | 0.28 |
| Ca I    | 4  | 5.63 | 0.11 | $-0.73$ | 0.20 | 4  | 5.35 | 0.17 | $-1.01$ | $-0.01^i$ |
| Ca II   | 4  | 5.62 | 0.13 | $-0.74$ | 0.18 | 3  | 5.43 | 0.25 | $-0.93$ | 0.07 |
| Sc II   | ... | ... | ... | ... | ... | 4  | 2.41 | 0.07 | $-0.76$ | 0.24 |
| Ti II   | 2  | 4.15 | 0.08 | $-0.87$ | 0.05 | 10 | 3.97 | 0.12 | $-1.05$ | $-0.05^i$ |
| Cr II   | 3  | 4.87 | 0.11 | $-0.78$ | 0.14 | 14 | 4.76 | 0.09 | $-0.91$ | 0.09 |
| Fe I    | 11 | 6.60 | 0.11 | $-0.90$ | 0.02 | 40 | 6.53 | 0.12 | $-0.97$ | 0.03 |
| Fe II   | 7  | 6.57 | 0.18 | $-0.93$ | $-0.02$ | 15 | 6.46 | 0.17 | $-1.04$ | $-0.04$ |
| Y II    | 5  | 3.02 | 0.20 | 0.78 | 1.70 | 10 | 2.85 | 0.15 | 0.61 | 1.61 |
| Zr II   | 1  | 3.09 | 0.49 | 1.42 | 8  | 3.02 | 0.15 | 0.42 | 1.42 |
| Ba II   | 3  | 4.78 | 0.07 | 2.65 | 3.58$^c$ | 1  | 2.45 | ... | 0.32 | 1.32 |
| La II   | 4  | 2.61 | 0.12 | 1.39 | 2.32 | 7  | 2.09 | 0.15 | 0.87 | 1.87 |
| Ce II   | 10 | 2.78 | 0.19 | 1.23 | 2.16 | 17 | 2.02 | 0.16 | 0.47 | 1.47 |
| Nd II   | 10 | 2.53 | 0.16 | 1.03 | 1.95 | 15 | 2.14 | 0.15 | 0.64 | 1.64 |
| Sm II   | ... | ... | ... | ... | ... | 5  | 1.26 | 0.11 | 0.25 | 1.25 |
| Eu II   | ... | ... | ... | ... | ... | 1  | 0.03 | ... | $-0.48$ | 0.52 |

$^a$ Does not include non-LTE correction of $-0.3$ dex; see text for details.

$^b$ Does not include non-LTE correction of $-0.4$ dex; see text for details.

$^c$ Abundance is derived using very strong ($W_\lambda > 400$ mA) Ba II lines.

have not applied them to the abundance values listed in Table 3. In the case of the O I abundance determined from the λ6156 triplet, the deviations from LTE were found to be not significant ($<0.1$ dex) in stars similar to those in this study (Takeda & Takeda-Hidai 1998).

4.4.2. Metals

The metallicity was determined using neutral and ionized iron peak lines of $W_\lambda \leq 100$ mA. Both of these stars were found to be metal-poor, with $[\text{Fe}/H] = -0.9$ for IRAS 06530–0213 and $[\text{Fe}/H] = -1.0$ for HD 56126. The abundances of other species like Ca, Sc, Ti, and Cr support the metal deficiency in these two stars. The recent non-LTE study of Rentzsch-Holm (1996) suggests a positive non-LTE correction to the LTE Fe abundance. For a group of A–F stars, this study revealed that non-LTE effects are significant for metal-poor and low-gravity stars as a result of overphotoionization and low collisional rates, respectively; it indicates a non-LTE correction of approximately +0.1 dex for a star having physical parameters similar to the stars in our study. This is within the uncertainties of the Fe abundance, and no correction was applied.

4.4.3. s-Process Elements

The abundances were determined for several s-process elements: Y, Zr, Ba, La, Ce, Nd, Sm, Eu, and Dy for HD 56126 and Y, Ba, La, Ce, Pr, and Nd for IRAS 06530–0213. In the case of HD 56126, the abundance results are based on many weak lines for each species, but this was not possible in the case of IRAS 06530–0213, since we were not able to find as many weaker lines ($W_\lambda < 150$ mA). This limitation for IRAS 06530–0213 seems to be due partly to its larger enhancement in the heavy elements (see Fig. 2) and partly to its more limited spectral range in the blue. Both stars are very abundant in s-process elements as compared with iron, with average values of $[s/\text{process}/\text{Fe}] = 1.9$ for IRAS 06530–0213 and $[s/\text{process}/\text{Fe}] = 1.6$ for HD 56126. Note that very strong Ba lines ($W_\lambda \geq 450$ mA) are present in the spectra of IRAS 06530–0213 and the derived abundances might be an overestimate (Table 3). Thus, we did not include the Ba abundance in computing the s-process average for this star.

4.4.4. Comparison with Recent Study of IRAS 06530–0213

An abundance analysis of IRAS 06530–0213 has recently been carried out by Reyniers (2002). This is based on high-resolution, high-S/N spectra obtained with the ESO 8 m VLT. Our atmospheric models are in good agreement except for $T_{\text{eff}}$, for which our model is cooler by 350 K; this results in a significantly lower metallicity ([Fe/H] = $-0.9$ vs. $-0.5$ for Reyniers). However, the abundances relative to Fe ([X/Fe]) are in good agreement. Thus, he similarly finds the object to be carbon-rich and overabundant in s-process elements.

4.4.5. Comparison with Previous Studies of HD 56126

HD 56126 has been previously analyzed by Parthasarathy, Garcia-Lario, & Pottasch (1992), Klochkova (1995), and more recently Van Winckel & Reyniers (2000), and the present results can be compared with the results of these studies. Klochkova, with spectra of $R \approx 24,000$ in the red, determined atmospheric parameters similar to ours; she found $T_{\text{eff}} = 7000$ K, $\log g = 0.1$, and $\xi_t = 5.5$ km s$^{-1}$. Our results for the abundances of C, N, O, Sc, and Fe are in general agreement with the values of Klochkova. However, we find the abundances of Mg, Si,
Ca, Ti, and Cr to be significantly less (>0.5 dex) than the values she derived, with our values being more consistent with the low metallicity of HD 56126. We also obtain similar values to Klochkova for the abundances of the ionized species of the s-process elements (Y, La, Nd). The recent study of Van Winckel & Reyniers (2000) is based on spectra with a similar resolution as in our study and includes an even larger spectral range resulting in the measurement of an even larger number of good lines (343 compared with 207 in our study). Their atmospheric model is identical to ours; they find $T_{\text{eff}} = 7250$ K, $\log g = 0.5$, $\zeta = 5.0 \text{ km s}^{-1}$, and $[\text{M/Fe}] = -1.0$. Our results are in good agreement with theirs; they obtain $[\text{C/Fe}] = +1.08$, $[\text{N/Fe}] = +0.85$, and $[\text{O/Fe}] = +0.81$. For the cases in which our results differ from those of Klochkova, they are in agreement with those of Van Winckel & Reyniers (2000). Our results show excellent agreement with Van Winckel & Reyniers (2000) in the high abundance of s-process elements, with an average difference of only +0.12 dex for the six such elements we have measured in common (for which more than one line was measured). Parthasarathy et al. (1992) only obtained spectra around eight particular wavelength settings in the red, with a range of 50–60 Å each, and thus their spectral coverage is small. Their spectra have a resolution of ~55,000 at Hα. They ran a series of models, including one close to ours: $T_{\text{eff}} = 7000$ K, $\log g = 0.5$, and $\zeta = 4 \text{ km s}^{-1}$. Our results for N and O are in good agreement with their values, but our abundances of C and Ca differ from theirs by roughly −0.5 dex, and we do not find the large S overabundance that they claim (based on only one line). In summary, our results are in good agreement with those of Van Winckel & Reyniers (2000) but differ in important ways from the lower resolution study of Klochkova (1995) and the limited spectral study of Parthasarathy et al. (1992). Hereafter, we discuss only our current results for this star.

4.5. Uncertainties

The uncertainties in the derived abundances due to the line-to-line scatter, $\sigma$, are attributed to the uncertainties in the measurements of the $W_{\lambda}$ and to the accuracy of the gf-values. These are listed in Table 3, and the consequent uncertainty in the abundance value is $\sigma/\sqrt{n}$. For the abundances derived from fewer than three lines of a species, we assume a realistic uncertainty to be 0.20 dex.

The uncertainties in the abundance values due to uncertain model parameters were computed for both stars. The uncertainty in $\zeta_i$ ($\pm 0.5 \text{ km s}^{-1}$) has little effect on the abundances (<0.05 dex). This is largely due to our use of weak lines in the analysis. The uncertainty in $\log g$ ($\pm 0.5$ dex) has a larger effect, typically $\pm 0.1$ but reaching around $\pm 0.2$ in a few cases (N i, Na i, Mg i, Ca i, Fe i). The uncertainty in $T_{\text{eff}}$ ($\pm 250$ K) has the largest effect, typically $\pm 0.1$ to $\pm 0.2$ dex for most of the elements and around $\pm 0.3$ dex for the s-process elements.

4.6. Hα, Na, and K Profiles

The strongest features in both spectra are the Hα and Na D1 and D2 lines. The Hα lines display shell-like emission profiles with a central absorption and are shown in Figure 6. This sort of Hα profile, a central absorption within the emission, we have found to be common in PPNs of F spectral type.

Previous studies of the Hα profile in HD 56126 have been published (Oudmaijer & Bakker 1994; Lèbre et al. 1996; Barthès et al. 2000). They all show a shell-like profile that is found to vary over a timescale of weeks. While an indication of two absorption components is seen in many of the published profiles, in our new spectrum of 1997 October 17 they are more clearly resolved. A difference of 34.9 km s$^{-1}$ is measured for the two components. The spectrum of 2002 November 14 shows instead a typical shell spectrum, with emission peaks of approximately equal heights on both sides of a deep absorption feature. Several studies have attributed this variable Hα emission to atmospheric pulsations and the propagation of associated shock waves through the photosphere, which generate emission with some self-absorption (Lèbre et al. 1996; Jeannin et al. 1996). Pulsations have been deduced from the observations of light and velocity variability, with a period of 37 days cited by Barthès et al. (2000). For IRAS 06530–0213, the two spectra obtained at different times appear very similar.

The Na D profiles are very strong in the spectra of IRAS 06530–0213 and HD 56126, reaching depths of 0.1 compared to the normalized continuum. This spectral region is displayed for both stars in Figure 7, with the Na D1 and D2 line profiles superimposed to show their similarities. The expected positions of the photospheric and circumstellar components are indicated in the figure, based on the derived velocities of atomic and molecular (§ 4.7) absorption lines, respectively. For IRAS 06530–0213, the nearly constant strengths of these very broad profiles suggest that they are all saturated. Analysis of the D1 and D2 profiles for this object leads to the suggestion that there may be as many as six different absorption components with overlapping profiles, which makes it difficult to derive quantitative results. The photospheric and circumstellar absorption lines appear...
to be embedded in a forest of interstellar Na lines. These are likely to be due to foreground interstellar clouds, given the low Galactic latitude \((b = -0.1)\) of IRAS 06530–0213, and their velocity differences are too small to be resolved in our spectra. For HD 56126, the photospheric absorption component and a strong circumstellar component are seen, along with three interstellar components \((V_r = 12, 23, 30 \text{ km s}^{-1})\). Similar results were found by Bakker et al. (1996). The circumstellar component has a velocity of 74.0 km s\(^{-1}\).

The profiles of neutral K at 7700 Å for both the stars are shown in Figure 8. Each profile shows a strong and a weak component. For each star, the weaker component agrees with the radial velocity of the photosphere and the stronger component agrees with the velocity of the cooler CSE (see Table 4). The stronger component in IRAS 06530–0213 is slightly asymmetric and appears to be blended with another component shifted 10 km s\(^{-1}\) blueward. Ultra–high-resolution spectral observations of HD 56126 by Crawford & Barlow (2000) have resolved this circumstellar K \(\text{I} \) line into two (or perhaps three) components with a velocity difference of 1.0 km s\(^{-1}\); they interpret this as due to discrete shells in the CSE.

We also searched for diffuse interstellar bands (DIBs) in the spectra of these two stars. No DIBs were found in the spectra of HD 56126. However, strong DIB features were identified in the spectra of IRAS 06530–0213 at 5780.41, 5797.0, 6376.1, and 6379.3 Å. Some of these are shown in Figure 9. The radial velocities of the DIBs are similar to those of the photospheric lines and differ from those of the CSE.

| COMPONENT | \(V_r\) (km s\(^{-1}\)) | \(V_{\text{exp}}\) (km s\(^{-1}\)) | \(V_r\) (km s\(^{-1}\)) | \(V_{\text{exp}}\) (km s\(^{-1}\)) | \(V_r\) (km s\(^{-1}\)) | \(V_{\text{exp}}\) (km s\(^{-1}\)) | \(V_r\) (km s\(^{-1}\)) | \(V_{\text{exp}}\) (km s\(^{-1}\)) |
|----------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Phot (atomic lines) | 51.0 ± 1.0 | ... | 50.4 ± 1.0 | ... | 83.3 ± 0.5 | ... | 86.2 ± 0.5 | ... |
| System (CO) | 50\(^{a}\) | ... | 50\(^{a}\) | ... | 87\(^{b}\) | ... | 87\(^{b}\) | ... |
| CSE (CO) | ... | \(\sim 10^{a}\) | ... | \(\sim 10^{a}\) | ... | ... | 10.2\(^{b}\) | ... | 10.2\(^{b}\) |
| CSE (C\(\text{II}\)) | 36.0 ± 0.6 | 14 | 36.4 ± 0.8 | 14 | 77.3 ± 0.5 | 10 | 76.6 ± 1.0 | 11 |
| CSE (CN) | 37.4 ± 1.5 | 13 | 37.4 ± 1.0 | 13 | 77.2 ± 0.5 | 10 | 76.1 ± 1.0 | 11 |
| CSE (Na \(\text{I}\)) | ... | ... | ... | ... | 74.0 ± 0.5 | 13 | 76.5 ± 1.0 | 11 |
| CSE (K \(\text{I}\)) | 34.0 ± 1.0 | 16 | ... | ... | 75.5 ± 1.0 | 12 | 76.1 ± 1.0 | 12 |

\(^{a}\) Hu et al. 1994, transformed from \(V_{\text{LRS}} = 33 \text{ km s}^{-1}\).

\(^{b}\) Omont et al. 1993, transformed from \(V_{\text{LRS}} = 73 \text{ km s}^{-1}\).
circumstellar molecular lines. These results differ from the those of the four PPNs studied by Klochkova, Panchuk, & Szczerba (2001); they concluded that DIBs formed (mainly) in the CSEs. Since the DIBs are not expected to form in the photospheres of these stars, we interpret the results in the CSEs. Since the DIBs are not expected to form in the photospheres of these transition objects are known to pulsate with amplitudes of several kilometers per second (Hrivnak & Lu 1999; Barthès et al. 2000), we will assume that the previously measured CO velocity is the system velocity. This results in an envelope expansion velocity of \( V_{\text{exp}} = 13 \text{ km s}^{-1} \). The velocities were similarly measured for these bands in HD 56126. The measured CO velocity \( V_r = 87.5 \text{ km s}^{-1} \) (\( V_{\text{LRS}} = 73 \text{ km s}^{-1} \); Omont et al. 1993) and our measured CSE molecular lines would result in \( V_{\text{exp}} = 10 \text{ km s}^{-1} \) for HD 56126. The measured expansion velocities are summarized in Table 4, and they are typical of the expansion velocities found for PPNs. (For other PPN expansion velocities based on visible spectra, see Bakker et al. 1997 and Reddy, Bakker, & Hrivnak 1999.)

5. DISCUSSION

As part of an ongoing, multiwavelength effort to identify and study PPNs, we have analyzed our observations of IRAS 06530–0213. The object is shown to be similar spectroscopically to the well-studied, carbon-rich PPN HD 56126 and to possess various characteristics of a PPN. These include a double-peaked SED, an expanding CSE, and the general abundance pattern of a post-AGB object; we will elaborate on these below. In addition, a small (2\(^2\) × 1\(^2\)) bipolar reflection nebula is seen around IRAS 06530–0213 in visible light (Ueta, Meixner, & Bobrowsky 2000).

5.1. Spectral Energy Distribution

Combining this new visible and near-infrared photometry with the \textit{IRAS} flux measurements, the SED of IRAS 06530–0213 can be delineated. This is shown in Figure 11. One can clearly see the double-peaked shape of the SED, with one peak arising from the reddened photosphere and a larger one from the circumstellar dust. Since the object is in

\[ T_d = 3090 \pm 100 \text{ K} \]

\[ T_{\text{dust}} = 170 \text{ K} \]

\[ T_{\text{dust}} = 2500 \text{ K} \]

\[ \lambda = 0.1 \mu \text{m} \]

\[ 1.0 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \]

\[ 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \]

\[ 10^{-7} \text{ erg cm}^{-2} \text{ s}^{-1} \]

\[ \text{ (solid line) } \]

\[ \text{ (dashed line) } \]

\[ \text{ (dot-dashed line) } \]

\[ \text{ (dash-dotted line) } \]

\[ \text{ (dotted line) } \]

\[ \text{ (dashed curve) } \]

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\[ \text{ (dashed curve) } \]
the Galactic plane \((l = 215^\circ, b = -0^\circ 1)\), some of the reddening and extinction will be caused by interstellar dust. Also shown is the SED corrected for this. An estimated value of \(A_V \approx 1.0\) mag was determined from the interstellar extinction study of Neckel & Klare (1980), and the interstellar extinction law of Cardelli, Clayton, & Mathis (1989) was applied. The fitted (reddened) photospheric temperature is \(T_{\text{fit}} = 2500\, \text{K}\), rising to \(T_{\text{fit}} = 2800\, \text{K}\) when corrected for interstellar extinction; thus, significant circumstellar reddening exists. The dust temperature is \(T_d = 170\, \text{K}\). The total flux from the dust component is \(\sim 5 \times 10^{-9}\, \text{ergs cm}^{-2}\, \text{s}^{-1}\), while the flux from the photosphere is one-fifth this amount. These values are based on blackbody fits to the SED. These lead to an observed luminosity of \(\sim 180(D/\text{kpc})^2\, \text{L}_\odot\). The SED of HD 56126 is similar in appearance, although there the two peaks are of similar height (Hrivnak, Kwok, & Volk 1989). A detailed modeling of the SED of HD 56126 found \(T_d = 165\, \text{K}\) and an observed luminosity of \(\sim 1400(D/\text{kpc})^2\, \text{L}_\odot\) (Hrivnak, Volk, & Kwok 2000). Thus, if the two objects have the same intrinsic luminosity, IRAS 06530–0213 is 2.8 times as distant.

5.2. Circumstellar Envelope

The CSE of IRAS 06530–0213 had previously been detected in CO (2–1) millimeter line emission at 1.3 mm (Hu et al. 1994). In these new high-resolution spectroscopic observations, the CSE is detected by its absorption of stellar light in the molecular lines of C2 and CN and in an atomic line of K I. The expansion velocities determined from these are in the range 13–16 km s\(^{-1}\); these are slightly larger than the cited expansion velocity of 10 km s\(^{-1}\) determined from the CO millimeter line observations. However, the latter value is measured as half of the total width of the CO emission feature, and visual inspection of the published CO spectrum shows that it is noisy and may well be larger than 10 km s\(^{-1}\). The expansion velocity for HD 56126 is slightly lower, \(V_{\text{exp}} = 10–13\, \text{km s}^{-1}\) as measured from the new C2, CN, K I, and Na I spectral observations; this is in very good agreement with \(V_{\text{exp}} = 10.2\, \text{km s}^{-1}\) measured from the millimeter line CO observations (Omont et al. 1993).

5.3. General Abundance Patterns

The abundances of CNO elements are crucial in determining the stellar evolutionary phase and the internal mixing and nucleosynthesis processes. The enhancement of the CNO elements in the photospheres of HD 56126 and IRAS 06530–0213 is a clear indication that these stars are evolved. Both the stars are found to have excess total CNO abundance \((\Delta \text{CNO}_{\text{obs}} = 8.9\) for IRAS 06530–0213, 8.7 for HD 56126) relative to the expected value \((\Delta \text{CNO}_{\text{exp}} = 8.20)\). The expected value was determined by assuming initial values of \([\text{C}/\text{Fe}] \approx 0.2\) (Gustafsson et al. 1999), \([\text{O}/\text{Fe}] \approx 0.40\) (Nissen et al. 2002), and \([\text{N}/\text{Fe}] \approx 0.0\). The first dredge-up in the red giant branch (RGB) phase and the second dredge-up in the AGB phase alter the C, N, and perhaps O abundances while keeping the total CNO abundance unchanged. An excess total CNO abundance indicates that a star has experienced the third dredge-up, which mixes freshly produced He-burning products into the photosphere. An examination of the individual C, N, and O abundances in Table 3 shows that all three elements are significantly overabundant relative to iron. An enhancement of C is expected as a result of the burning of He via the triple-\(\alpha\) reaction and the deep convection during the AGB phase, and an enhancement of N is expected as a result of the CN reaction during both the RGB and AGB phases. Interestingly, O is overabundant in both stars, especially in HD 56126. In the case of IRAS 06530–0213, the value of \([\text{O}/\text{Fe}] = 0.5\) is consistent with the chemical evolution of the Galaxy. The value of \([\text{O}/\text{Fe}] = 0.7\) in HD 56126 is 0.3 dex in excess of the expected initial O abundance. Since it is the ratio of abundances, an uncertainty in the \([\text{O}/\text{Fe}]\) ratio as a result of uncertainties in the model parameters is small \((\pm 0.1\, \text{dex})\) and non-LTE effects are small \((\approx 0.01; \S\; 4.4.1)\). It is possible that the O overabundance in HD 56126 is the result of AGB mixing. The He triple-\(\alpha\) in the interiors of AGB stars results in the production of additional C, and the additional O may be produced as a result of the \(^{12}\text{C}(\alpha, \gamma)^{16}\text{O}\) reaction. While standard convective mixing models do not predict an overabundance of O in the photosphere, mixing models with convective overshoot do predict a significant enhancement of both C and O (Herwig et al. 1997). Thus, the overabundances of both C and N indicate that IRAS 06530–0213 has evolved through the RGB and AGB phases of evolution similar to HD 56126, and the overabundance of O is consistent with this.

Among \(\alpha\)-process elements, abundances of Mg, Si, Ti, and Ca were measured for IRAS 06530–0213 (Mg, Si, S, Ca, and Ti for HD 56126), and these are found to be normal relative to Fe for stars of \([\text{Fe}/\text{H}] = -1.0\). Slight overabundances of some of these elements are consistent with the Galactic chemical evolution (see Chen et al. 2002).

The enhancement of heavy elements like Y, Zr, Ba, La, etc., is one of the distinctive features of the photospheres of AGB/post-AGB stars. These elements are produced by iron-seed nuclei capturing neutrons slowly relative to \(\beta\)-decay (the “\(s\)-process”). In low-mass AGB stars neutrons are mainly produced from the reaction \(^{12}\text{C}(\alpha, n)^{16}\text{O}\) (Iben 1983). This is accomplished by the diffusion of protons downward into the He shell where they are captured by the abundant \(^{12}\text{C}\), producing a sufficient amount of \(^{13}\text{C}\). The heavy elements produced in the interior are brought to the photosphere through the third dredge-up during the thermally pulsing AGB phase.

The particular importance of measuring the abundance of the \(s\)-process elements is that this can be used to determine a star’s particular phase of evolution and also to better understand the nucleosynthesis processes (from the \(s\)-process elemental distribution). The large enhancements in the observed \(s\)-process elements in IRAS 06530–0213 \((\Delta [\text{s-process}/\text{Fe}] = 1.9)\) and HD 56126 \((\Delta [\text{s-process}/\text{Fe}] = 1.6)\) fall in the range of values of 0.9–2.2 measured in other PPNs (Reddy et al. 1999, 2002; Van Winckel & Reyniers 2000). This is consistent with the other evidence that these two F-type supergiants are indeed post-AGB stars and have experienced \(s\)-process nucleosynthesis and deep convective mixing on the AGB phase of evolution.

To better interpret the observed \(s\)-process elements, following the definition of Luck & Bond (1991), one can derive the ratio of heavy-to-light \(s\)-process elements, \([\text{hs}/\text{ls}] = [\text{hs}/\text{Fe}] - [\text{ls}/\text{Fe}]\), where \([\text{hs}/\text{Fe}]\) and \([\text{ls}/\text{Fe}]\) are the average heavy (La, Ce, Nd) and light (Y, Zr) \(s\)-process elemental abundances, respectively, relative to Fe. This ratio represents the \(s\)-process distribution; the higher this ratio, the higher the value of the neutron exposure \(\tau_n\). The values of \(\tau_n\) were derived using the theoretical computations of Busso et al. (1995) for exponential distribution models.
of neutron density \( N_n = 10^8 \text{ cm}^{-3} \). For HD 56126, [hs/ls] = +0.1, which corresponds to \( \tau_m \approx 0.4 \), while for IRAS 06530–0213, [hs/ls] = 0.5, which suggests a neutron exposure rate of \( \tau_m \approx 1.0 \).

The value of [hs/ls] = 0.5 for IRAS 06530–0213 is among the largest found for a PPN and is similar to the result for IRAS 22272+5435 and IRAS 05113+1347 (Reddy et al. 2002). With its associated large overabundance of \( s \)-process elements, IRAS 06530–0213 follows the tight correlation between these two parameters found for six other C-rich PPNs by Van Winckel & Reyniers (2000). This PPN also follows the correlation of increasing [hs/ls] with decreasing metallicity [Fe/H] (Reddy et al. 2002) and fits closely to the predicted theoretical curve (Busso et al. 2001). Thus, IRAS 06530–0213 fits well with the \( s \)-process distribution and metallicity relations found for other PPNs.

6. CONCLUSIONS

Atmospheric parameters and elemental abundances of C, N, O, iron peak, and \( s \)-process elements were derived for IRAS 06530–0213 based on high-resolution spectra and LTE model atmosphere analysis. Model atmospheric parameters \( T_{\text{eff}} = 6900 \text{ K}, \log g = 1.0, \) and \( \xi_t = 4.5 \text{ km s}^{-1} \) were determined. The star is metal-poor ([Fe/H] = −0.9), carbon-rich (C/O = 2.6), and enhanced in C ((C/Fe) = 1.3), N ((N/Fe) = 1.0), and \( s \)-process elements ([\( s \)-process/Fe] = 1.9). These abundance results imply that IRAS 06530–0213 is a low-mass, carbon-rich, post-AGB star that has passed through the third dredge-up on the AGB. It is similar to the well-studied, C-rich PPN HD 56126.

Circumnuclear molecular (C\(_2\) and CN) and atomic (K \(_{\text{i}}\)) features were measured that reveal the gaseous component of the expanding CSE. System and circumstellar expansion velocities of \( V_r = 51 \text{ km s}^{-1} \) and \( V_{\text{exp}} = 14 \text{ km s}^{-1} \), respectively, were found. These are in general agreement with previous millimeter-wave CO measurements.

IRAS 06530–0213 can thus be added to the small group of approximately a dozen identified carbon-rich PPNs. Like them, it is metal-poor with a large overabundance of \( s \)-process elements. Since the other objects in this small group of carbon-rich PPNs all show the 21 \( \mu \text{m} \) emission feature (except for perhaps IRAS 07430+1115; Hrivnak & Kwok 1999), it is likely that IRAS 06530–0213 does also. The infrared spectrum of the object existing in the IRAS Low-Resolution Spectrometer database is too noisy to judge the presence of the 21 \( \mu \text{m} \) feature, and the position of the object in the sky made it inaccessible to observation with the Infrared Space Observatory. Thus, the presence of the expected 21 \( \mu \text{m} \) feature and also the 30 \( \mu \text{m} \) feature seen in carbon-rich evolved stars remain to be confirmed.

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REFERENCES

Allende Prieto, C., Lambert, D. L., & Asplund, M. 2002, ApJ, 573, L137
Bakker, E. J. 1995, Ph.D. thesis, Univ. Utrecht
Bakker, E. J., van Dishoeck, E. F., Waters, L. B. F. M., & Schoenmaker, T. 1997, A&A, 323, 469
Bakker, E. J., Waters, L. B. F. M., Lamers, H. J. G. L. M., Trams, N. R., & Van der Wolf, F. L. A. 1996, A&A, 310, 891
Barthès, D., Lèbre, A., Gillet, D., & Maunour, N. 2000, A&A, 359, 168
Blöcker, T. 1995, A&A, 299, 755
Busso, M., Gallino, R., Lambert, D. L., Travaglio, C., & Smith, V. V. 2001, ApJ, 557, 802
Busso, M., Lambert, D. L., Beglo, L., Gallino, R., Raiteri, C. M., & Smith, V. V. 1995, ApJ, 446, 771
Cardelli, J. A., Clayton, D. D., & Mathis, J. S. 1989, ApJ, 345, 245
Chen, Y. Q., Nissen, P. E., Zhao, G., & Asplund, M. 1999, A&A, 340, 242
Hrivnak, B. J. 1995, ApJ, 449, 839
Klochkova, V. G. 1995, MNRAS, 272, 710
Klochkova, V. G., Panchuk, V. E., & Szczerba, R. 2001, in Post-AGB Objects as a Phase of Stellar Evolution, ed. R. Szczerba & S. K. Gorny (Dordrecht: Kluwer), 265
Kwok, S. 1993, ARA&A, 31, 63
———. 2000, The Origin and Evolution of Planetary Nebulae (Cambridge: Cambridge Univ. Press)
Makishima, Y., & Makishima, K. 1999, in IAU Symp. 191, Asymptotic Giant Branch Stars, ed. T. Le Bertre, A. Lèbre, & C. Waelkens (San Francisco: ASP), in press
Nissen, P., Primas, F., Asplund, M., & Lambert, D. L. 2002, A&A, 390, 235
Ottewill, R. A., & Barlow, M. J. 2000, MNRAS, 311, 370
Panchuk, V. E., & Szczerba, R. 2001, in Post-AGB Objects as a Phase of Stellar Evolution, ed. R. Szczerba & S. K. Gorny (Dordrecht: Kluwer), 265
Reedy, B. E., & Reyniers, B. J. 1999, ApJ, 524, 831
Reddy, B. E., & Hrivnak, B. J. 1999, ApJ, 519, 883
Reddy, B. E., Bakker, E. J., & Hrivnak, B. J. 1999, ApJ, 518, 482
Reddy, B. E., & Barlow, M. J. 2000, MNRAS, 314, 314
Renzsch-Holm, I. 1996, A&A, 312, 425
Sivagnanam, P. 1993, A&A, 267, 515
Takada-Yamamoto, K., & Takeda-Hidalgo, M. 1998, PASJ, 50, 629
Van der Marel, R. A., & van der Marel, R. A. 2003, Abundance Analysis of IRAS 06530+20.0213
Van der Marel, R. A., & van der Marel, R. A. 2003, Abundance Analysis of IRAS 06530+20.0213
Van der Marel, R. A., & van der Marel, R. A. 2003, Abundance Analysis of IRAS 06530+20.0213
Venn, K. 1995, ApJ, 449, 839
Wiese, W. L., Fuhr, J. R., & Deters, T. M. 1996, Atomic Transition Tables, NBS Monogr. 61, Boulder, CO: US Gov. Printing Office
Winters, J., & Owocki, S. P. 1999, in IAU Symp. 191, Asymptotic Giant Branch Stars, ed. T. Le Bertre, A. Lèbre, & C. Waelkens (San Francisco: ASP), in press
Worseck, G., & Worseck, G. 1999, in IAU Symp. 191, Asymptotic Giant Branch Stars, ed. T. Le Bertre, A. Lèbre, & C. Waelkens (San Francisco: ASP), in press
Wood, W., & Sahai, R. 2000, ApJ, 528, 861
Wood, W., & Sahai, R. 2000, ApJ, 528, 861
Wood, W., & Sahai, R. 2000, ApJ, 528, 861
Wood, W., & Sahai, R. 2000, ApJ, 528, 861