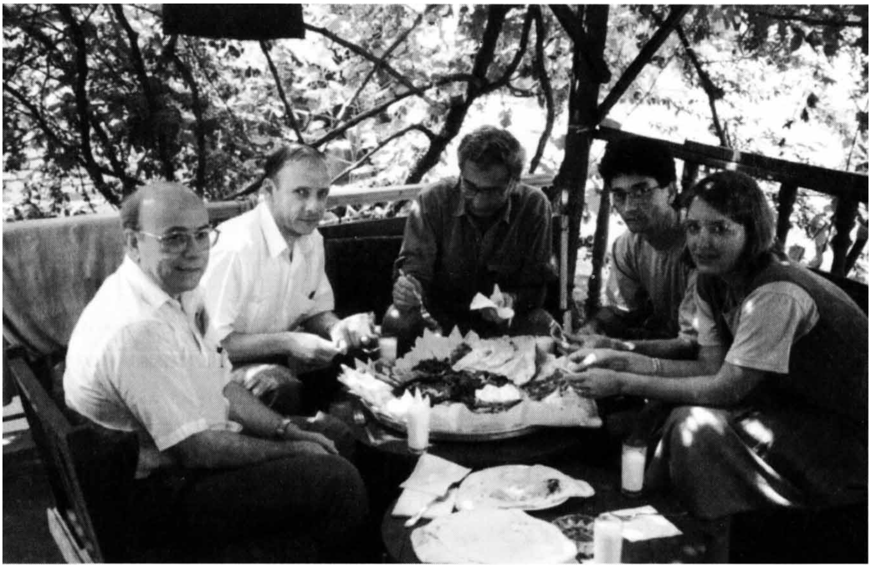
Session III

OBSERVED SPECTRA
AND
ENERGY DISTRIBUTIONS

Sunetra Giridhar relaxing with Ingrid Wing, Sylvia Önder, and baby Timur.



Jack MacConnell, Mário Magalhães, Jay Frogel, Muammer Önder, and Sylvia Önder enjoying a Turkish lunch, complete with *rakı*.

SPECTRAL CHARACTERISTICS OF RV TAURI STARS

SUNETRA GIRIDHAR
Indian Institute of Astrophysics
Bangalore, India

Abstract. Spectroscopic properties of RV Tau variables are summarized. We report on our detailed spectroscopic investigation of a sample of RV Tau stars covering all three RV Tau subgroups. Though the observed abundance pattern is similar to those of a few post–AGB stars, we find considerable variation in the observed chemical compositions indicating that there is some non-homogeneity among subgroups of RV Tau variables. Possible scenarios of dust–gas separation in the material ejected by the dusty wind are discussed to explain the observed abundances. This mechanism would work better if the star happens to possess a binary companion. Interestingly, one of our sample stars, EP Lyr, shows long-term variations in radial velocity possibly caused by the presence of a companion.

1. Introduction

The RV Tau stars have been classified as pulsating variables of Population II, but their light variations are not as regular as those of Type II Cepheids. They are post–AGB objects evolving off the AGB after mass loss has reduced the envelope mass to such an extent that the thermal flashes in the helium-burning region cannot be sustained, and they later end up as central stars of planetary nebulae. Figure 1 shows the color-magnitude diagram for the globular cluster M5 (Buonnano et al. 1981). The figure also shows the positions of several RV Tau stars and evolutionary tracks for 0.605 $M_\odot$ and 0.546 $M_\odot$ post–AGB models by Schönberner (1993). The positions of these well-known RV Tau stars in Fig. 1 substantiate the view that these are post–AGB stars.

The important features of RV Tau stars can be summarized as follows. The light curves are very distinctive with alternating deep primary and shallow secondary minima. The period is defined as the time elapsed between the two consecutive deep minima. The observed periods are in the

R.F. Wing (ed.), The Carbon Star Phenomenon, 117-125.

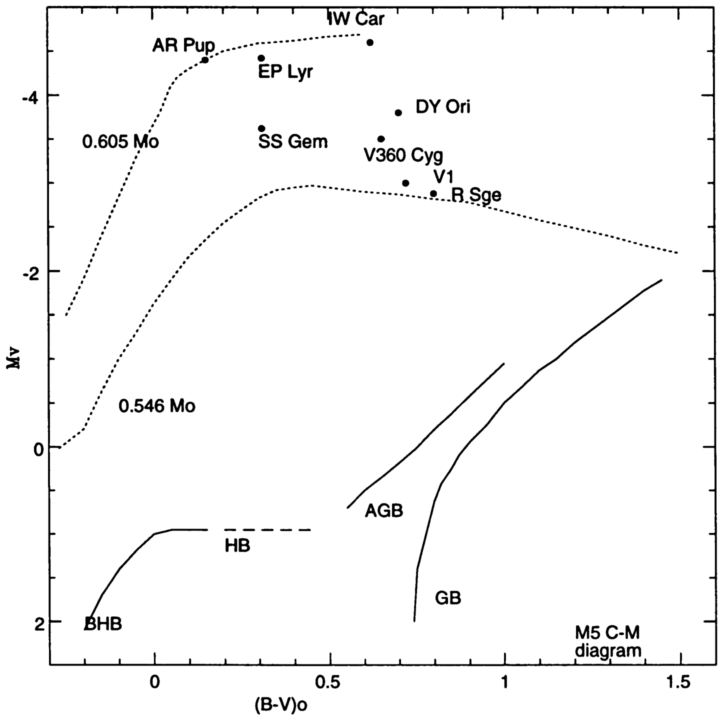


Figure 1. C–M diagram for M5 and positions of well-known RV Tau stars. The values of M_V for the RV Tauri stars were calculated by Gonzalez using the P–L relation for RV Tau stars described in Gonzalez (1994). The color excesses needed for calculating $(B–V)_o$ are taken from a number of sources that are listed in Gonzalez, Lambert & Giridhar (1997).

range of 30 to 150 days. Irregularities in the light period are noticed for many, but hotter members of the class generally have more stable periods. In the *General Catalogue of Variable Stars* (Kukarkin et al. 1969), RV Tau stars with constant mean brightness levels are classified RVa. RV Tauris for which the mean brightness varies with a longer period and with a larger amplitude of variation are classified RVb. An infrared excess is observed for most RV Tauris (Gehrz & Wolf 1970; Gehrz 1972). The infrared fluxes of RV Tauris show a peak near 11 μm for all RV Tau subgroups whereas a peak near 2–3 μm is seen only for RV Tauris with variable mean magnitude. These infrared excesses indicate the presence of circumstellar shells.

Preston et al. (1963) subdivided the RV Tauri stars into three spectroscopic groups (A, B, C) based on low-dispersion spectra. The RV A stars have spectra indicating spectral types G–K but abnormal strength of the CN bands or the G band of CH. Near light minimum, TiO bands of abnormal strength are seen. RV B stars show spectra of type F; the most interesting feature of these stars is the appearance of CH and CN bands that become very strong at light minimum. Though these stars generally seem to be metal-poor, numerous C I lines are seen at all phases. RV C stars are very similar to RV B stars but the CN and CH bands (the most remarkable features of group B stars) are either weak or absent at all phases. A few RV Tau stars belonging to globular clusters are found to be RV Tau stars of group C. An example is V1 in ω Cen, observed by Gonzalez & Wallerstein (1994).

The radial velocity varies in phase with the light variation, indicating a pulsational variation. However, it is difficult to draw a smooth radial-velocity curve as lines become double between phase 0.1 to 0.2. The line doubling of several strong lines and emission components in hydrogen lines are caused by the passage of a shock wave through the atmospheric layers.

The galactic latitudes of these stars are generally within $\sim 30°$ of the galactic plane. Estimates of Z (their distance from the galactic plane) range from 100 pc to 2 kpc. They appear likely to be a mixed population with a larger fraction being of the thick disk population. This view is also supported by the chemical composition studies as we shall see shortly.

1.1. CHEMICAL COMPOSITION

The chemical composition is an important datum for any kind of star. This is particularly so in the case of post–AGB stars where many processes may have affected the surface composition of the star, such as deep convective mixing or processes that might blow away a large fraction of the outer envelope exposing deeper layers. A complete abundance analysis covering elements formed by different nucleosynthesis chains and isotopic abundance ratios is mandatory for understanding the evolutionary history of the star and its current status.

In the case of RV Tau stars such attempts in the past have been few and none has really been complete. Besides, the older workers used outdated atomic data and analysis techniques and hence did not attain the desired accuracy. The study of AC Her by Baird (1979) is relatively better. The studies of R Sct by Luck (1981) and of U Mon and RU Cen by Luck & Bond (1989) use good-quality spectra and modern techniques, but they do not cover the light elements. Our study of the RV B star IW Car (Giridhar et al. 1994, hereafter Paper I) was perhaps the first comprehensive work on a field star using high-resolution and high S/N CCD spectra covering a large number of elements, and we found many intriguing features. The Fe-peak elements are deficient generally by an order of magnitude, but the elements S and Zn are almost solar. This pattern is also shown by a few high-galactic-latitude post–AGB stars. The abundance pattern of IW Car is not the one expected of a normal metal-poor star but it correlates well with the elemental depletions observed in the ISM, i.e. the elements with high condensation temperatures are strongly depleted. On the other hand Gonzalez & Wallerstein (1994) found evidence of CNO processing and enhancement of *s*-process elements for variable V1 in ω Cen though the star is generally metal-poor. We decided to explore this non-uniformity of chemical composition of RV Tau stars by studying a sample containing members of different light curve types, Preston spectral groups, periods, galactic latitudes, and infrared fluxes. Our initial sample is presented in Table 1.

TABLE 1. Basic parameters of the RV Tau program stars

Parameter	IW Car	V360 Cyg	SS Gem	EP Lyr	DY Ori	AR Pup	R Sge	V1 in ω Cen
$<V>$	8.5	11.3	8.9	10.4	11.7	9.6	9.3	11.0
$<B\text{–}V>$	0.83	0.94	1.07	0.76	(0.92)	0.76	1.07	0.6
Period (days)	67.5	70.4	89.3	83.4	60.3	38.9	70.6	58.7
Gal. lat. (°)	-9.2	-11.8	1.3	6.7	-3.4	-3.0	-9.8	15
IR excess	yes	no	yes	no	yes	yes	yes	no
Preston group	B	C	B	B	B	B	A	B–C
Var. type	RVb	RVa	RVa	RVa	?	RVb	RVb	RVa

The RV Tau star SS Gem deserves special mention. It was considered RV A by Preston et al. (1973), and subsequent papers have referred to it by the same spectroscopic designation. However, high resolution spectra of this star show numerous C I lines and also CH lines of moderate strength near 4290 Å. It is obviously an RV B star.

2. Observations and Abundance Determination

High-resolution spectra were obtained for over 1.5 years at the McDonald Observatory 2.10-m telescope with a Cassegrain echelle spectrograph and a Reticon 1200×400 pixel CCD. Generally a S/N ratio of 100 and two-pixel resolution of 50,000 was attained. Each star was observed at several epochs and care was taken in selecting phases when the atmosphere was not perturbed by the passage of a shock wave that manifests itself through distortions in Balmer lines and line doubling.

We have used an updated version of the LTE line-analysis program MOOG (Sneden 1973) that calculates the abundance for each spectral line individually or produces a synthesized spectrum of the required region.

We have used the new grid of model atmospheres by Kurucz (1992). The atmospheric parameters ($T_{\rm eff}$, log g, v_t) were determined from a set of Fe I and Fe II lines. The details of our method and error analysis can be found in Paper I; the results are summarized in Table 2.

TABLE 2. Derived abundances for the sample RV Tau stars

Element	T_c	EP Lyr	DY Ori	AR Pup	R Sge	IW Car	V1 ω Cen	SS Gem	V360 Cyg
O	200	−0.04	—	0.14	−0.64	−0.33	−0.68	−0.49	−0.22
C	90	−0.37	−0.18	0.05	−0.41	0.32	−1.07	−0.44	—
S	648	−0.61	0.16	0.44	0.37	0.36	−0.89	−0.22	−0.65
Zn	660	−0.70	0.21	—	−0.19	−0.04	−1.40	−0.36	−0.97
Na	970	−1.14	0.04	−0.15	0.10	0.34	−1.58	−0.11	−0.95
Mn	1190	−1.95	—	—	−0.16	—	—	−0.91	—
Cr	1277	−1.83	—	—	−0.28	−0.98	−1.43	−1.16	—
Si	1311	−1.26	−1.41	−0.39	0.08	−0.57	−1.12	−0.22	−1.08
Fe	1336	−1.80	−2.30	−0.87	−0.50	−1.06	−1.77	−1.00	−1.27
Mg	1340	−1.85	−2.11	−1.03	—	−0.98	−1.18	−0.55	—
Ca	1518	−1.82	−1.70	−1.37	−0.95	−1.97	−1.36	−1.24	−1.20
Ni	1354	−1.59	—	−1.30	−0.50	−0.96	−1.51	−1.03	−1.10
Ti	1549	−2.01	—	—	−1.34	—	−1.52	−2.11	—
Y	1592	−1.87	—	—	−1.68	—	−1.16	−1.46	—
Sc	1644	−2.11	—	−2.16	−1.48	−2.13	−1.91	−2.10	—

3. Results and Discussion

In Paper I we found that the abundance pattern for the RV Tau star IW Car is similar to that of post–AGB stars and that the abundances correlate very strongly with the elemental depletions observed in the ISM. The elements that condense more easily (i.e. with higher condensation temperature) are more strongly depleted. We have plotted in Figures 2 and 3 the abundances of our sample stars against the condensation temperature T_c, which is defined as the temperature at which half of a particular element in a gaseous environment condenses onto grains. We have adopted the values of T_c given by Wasson (1985) for the solar mix at a pressure of 10^4 atm, the pressure at which the data are most complete. As one can see the plots fall into two categories: (*a*) those with a single slope like EP Lyr, and (*b*) those like AR Pup showing a plateau up to $T_c = 1000\,$K, followed by a negative slope.

The abundances in field RV Tauri stars show a strong correlation with T_c, particularly for the elements with $T_c \geq 1000\,$K. These stars have nearly solar S and Zn but very low Ca, Sc, and Ti abundances. The depletions

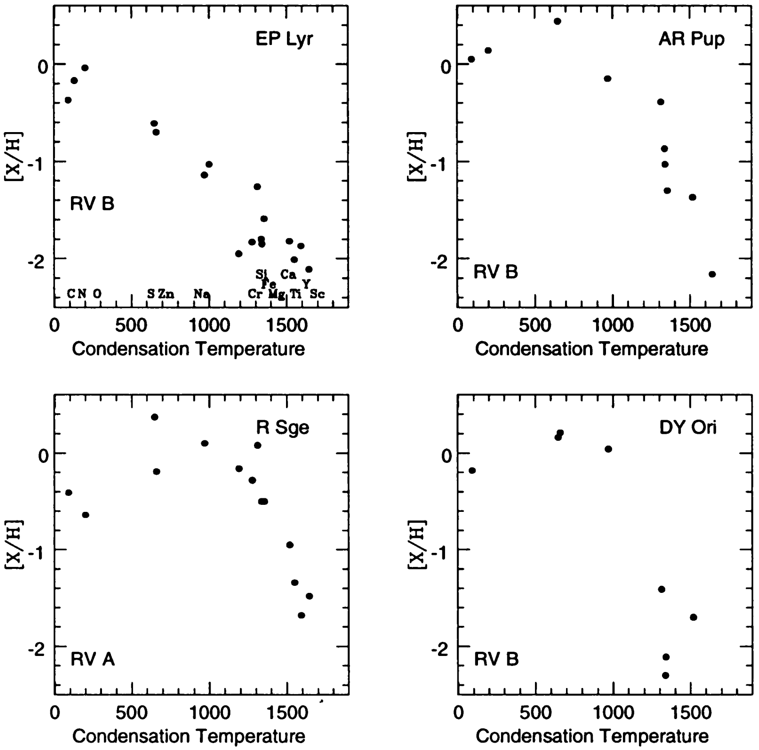


Figure 2. Relative abundances [X/H] *vs.* the condensation temperature T_c for EP Lyr, AR Pup, R Sge, and DY Ori.

show a very shallow correlation with T_c in the case of V1 in ω Cen. Even two moderately Fe-poor stars, AR Pup and R Sge, show better correlations of [X/H] with T_c. The abundance patterns of our sample stars are quite different from that found for unevolved or less evolved objects. Past abundance studies of large samples of such objects would have suggested for Fe-poor stars like EP Lyr and DY Ori ([Fe/H] ≈ -2) a value of [S/Fe] around +0.4 and of [Zn/Fe] around 0.0 instead of the values (1.2, 1.0) and (1.0, 2.5), respectively, observed for these stars. The abundance pattern of the sample RV Tau stars is also quite different from that of solar-metallicity supergiants.

3.1. INTERPRETATION IN TERMS OF DUST–GAS SEPARATION

As we mentioned earlier, an infrared excess is found for most RV Tau stars. Jura (1986) estimated the mass-loss rate from the 12 μm flux, an adopted emissivity of dust, an assumed outflow velocity of 10 km s^{-1}, and a distance

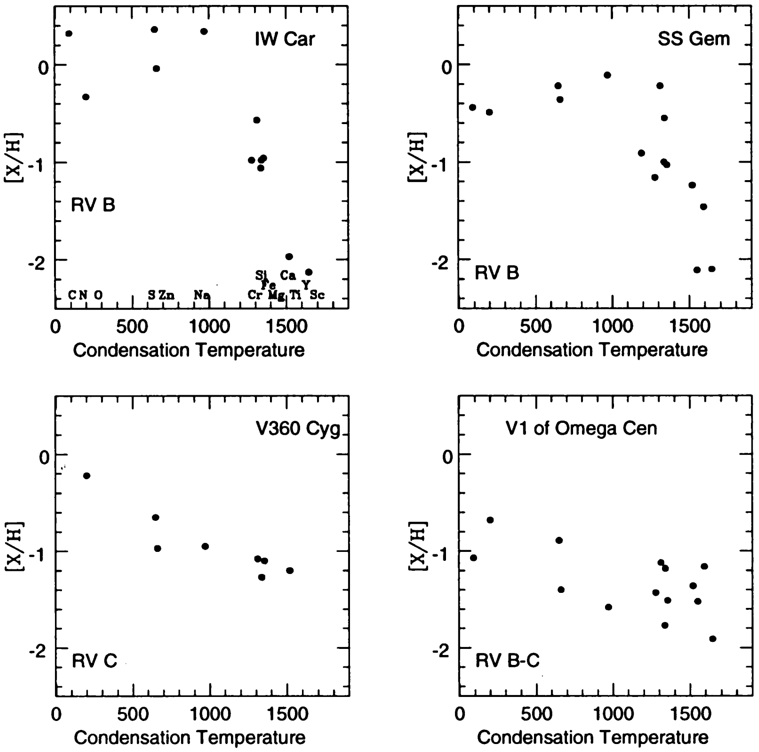


Figure 3. Relative abundances [X/H] *vs.* T_c for IW Car, V360 Cyg, SS Gem, and V1 in ω Cen.

calculated from a period-luminosity law. A typical value for the mass-loss rate for the dust is $\dot{m}(\mathrm{d}) \approx 10^{-8}\,M_\odot/\mathrm{yr}$. One expects the dust to drag along some gas. If the dust to gas ratio is 1% by mass, the total mass-loss rate $\dot{m}(\mathrm{d})+\dot{m}(\mathrm{g})$ would be $\approx 10^{-6}\,M_\odot/\mathrm{yr}$. This mass loss has to be fed by a stellar envelope. A star evolving from the AGB to the planetary nebula phase and the white dwarf cooling track has an envelope mass M_e of around $10^{-3}\,M_\odot$ (Schönberner 1981). Other RV Tau scenarios put them on blue-loops from the AGB to lower luminosities. Gingold (1974) modeled the post–AGB evolution of a $0.6\,M_\odot$ metal-poor star and found the envelope mass to be as small as $0.005\,M_\odot$ for the star to leave the AGB. Hence, the envelope masses are expected to be in the 0.005 to 0.001 $M_\odot$ range. A photosphere containing a mass $M_\mathrm{ph} = 10^{-6}\,M_\odot$ cannot feed the wind for long even if one considers only the mass-loss rate for dust alone. Consequently, it would progressively eat into the envelope. A change of chemical composition is probable since some elements condense more easily onto grains, and at lower gas densities the coupling of the gas to the grain will be weak. It is likely that a dusty wind will effect a chemical fractionation which, if gas falls back to the photosphere, will be reflected in the chemical composition of the photosphere. One can argue that the photospheres of RV Tauri stars are too warm to initiate dust formation, which in the outer and cooler layers the gas density in hydrostatic equilibrium may be too low to sustain a dusty wind. We propose that the pulsation characteristics of RV Tau variables periodically enhance the gas and dust densities at high altitudes. Between these episodes of replenishment of the gas, it is most likely that some gas may fall back into the photosphere. The impact of the fractionated gas on the chemical composition will be larger if the efficiency with which the base of the photosphere is mixed with the entire envelope is lower.

In the scenario of dust–gas separation, the photospheric abundance anomalies should correlate with conditions more favorable for elements to condense onto grains. A strong correlation between photospheric abundances and $T_{\rm c}$, first found for IW Car and later for EP Lyr and DY Ori, gives strong support to this mechanism. Then, it would appear that elements exhibiting little depletion in the ISM are a better indicator of the star's original metallicity. In this regard, S and Zn would be better metallicity indicators than even C, N, or O whose surface abundances get altered by nuclear reactions and dredge-up. Two stars, V360 Cyg and V1 of ω Cen, appear to be metal-poor as well as metal-depleted as indicated by their abundances of S and Zn relative to other elements more affected by condensation. Generally, the [X/H] *vs.* $T_{\rm c}$ diagram has a nearly flat portion and a sudden break at $T_{\rm c}$ around 1000 K (an exception is EP Lyr with a single slope). We might suggest that the distance at which the condensation took place will vary from star to star depending upon the existence of circumstellar matter (maintained far away due to the existence of a binary companion or via sporadic strong ejection of dusty wind). If condensation took place far away where the elements with lower $T_{\rm c}$ could condense, then depletion would be seen for all elements with similar or higher $T_{\rm c}$. Perhaps we are witnessing that effect in IW Car and EP Lyr. But if there is no way of maintaining circumstellar matter far from the star, then only the elements with $T_{\rm c} > 1000$ K or so will be depleted. Van Winckel et al. (1995) have proposed an attractive way of attaining dust–gas separation far from the star in a circumbinary disk with the main star accreting gas but not dust. That makes the search for stellar companions to RV Tau stars very important.

Spectroscopic observations of Gonzalez for EP Lyr spanning 1.5 years show an indication of velocity perturbation that is different from pulsation. The light curve of EP Lyr is very stable but still the spectra taken at nearly identical pulsation phases show a variation in heliocentric velocity ranging up to 30 $\mathrm{km\,s^{-1}}$. Both photometric and spectroscopic observations are being used to determine if the star indeed has a binary companion. But a similar search would be of great importance for other RV Tau stars showing a single slope in depletion diagrams, and long-term radial-velocity monitoring is advocated. The study of a larger sample of field and cluster members is essential for a better understanding of these fascinating objects.

The work presented here is part of an ongoing RV Tau program in collaboration with D. L. Lambert, N. Kameswara Rao and G. Gonzalez). I am grateful to Prof. Lambert for hospitality at the University of Texas at Austin as well as for a number of very important suggestions. It is a pleasure to thank Dr. Gonzalez for providing important data that went into the preparation of Figure 1. I also thank the IAU and INSA for supporting my visit to Turkey to attend IAU Symposium 177 on "The Carbon Star Phenomenon."

References

Baird, S. R. 1979, Ph.D. thesis, Univ. of Washington
Buonanno, R., Corsi, C. E. & Fusi Pecci, F. 1981, *MNRAS*, 196, 435
Gehrz, R. D. 1972, *ApJ*, 178, 715
Gehrz, R. D. & Woolf, N. J. 1970, *ApJ*, 161, L213
Gingold, R. A. 1974, *ApJ*, 193, 177
Giridhar, S., Kameswara Rao, N. & Lambert, D. L. 1994, *ApJ*, 437, 476 (Paper I)
Gonzalez, G. 1994, *AJ*, 108, 1312
Gonzalez, G., Lambert, D. L. & Giridhar, S. 1997, *ApJ*, 479, 427
Gonzalez, G. & Wallerstein, G. 1994, *AJ*, 108, 1325
Jura, M. 1986, *ApJ*, 309, 732
Kukarkin, B. V., Kholopov, P. N., Efremov, Yu. N., Kukarkina, N. P., Kurochkin, N. E., Medvedeva, G. I., Perova, N. B., Fedorovich, V. P. & Frolov, M. S. 1969, *General Catalogue of Variable stars*, Moscow.
Kurucz, R. L. 1992, private communication
Luck, R. E. 1981, *PASP*, 93, 211
Luck, R. E. & Bond, H. E. 1989, *ApJ*, 342, 476
Preston, G. W., Krzeminski, W., Smak, J. & Williams, J. A. 1963, *ApJ*, 137, 401
Schönberner, D. 1981, *A&A*, 103, 119
Schönberner, D. 1993, in IAU Symp. 155: *Planetary Nebulae*, ed. R. Weinberger and A. Acker (Kluwer), p. 415
Sneden, C. 1973, Ph.D. thesis, Univ. of Texas at Austin
Van Winckel, H., Waelkens, C. & Waters, L.B.F.M. 1995, *A&A*, 293, L25
Wasson, J. T. 1985, *Meteorites: Their Record of Early Solar-System History* (New York: W. H. Freeman)