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THE PECULIAR PLANETARY NEBULA IN M22

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ABSTRACT

The source discovered by the *IRAS* satellite near the center of the globular cluster M22, IRAS 18333−2357, has been studied using the *IUE* satellite and a ground based optical telescope. The northern component of the close pair of stars is not a member of the cluster. The southern component is a hot star with $T_{\text{eff}} \approx 50{,}000$ K illuminating a small planetary nebula and is a member of M22. Both the planetary nebula (PN) and its central star are extremely hydrogen deficient. The luminosity of the central star is in good agreement with that expected on theoretical grounds and with the observed luminosity of the tip of the red giant branch.

Subject headings: clusters: globular — infrared: sources — nebulae: planetary — ultraviolet: spectra

I. INTRODUCTION

A strong far-infrared source was discovered near the center of the globular cluster M22 by the *IRAS* satellite. Gillett *et al.* (1989) found the optical/infrared counterparts, which are a pair of stars separated by 1″.3, together with a small planetary nebula. These objects had several peculiarities which merit further investigation. Critical unresolved issues include the nature and luminosity of the extremely blue star which is one component of the pair, whether the red component is a member of the cluster M22, and the peculiar abundances implied by the very unusual spectrum of the planetary nebula, which shows in the optical spectral regime only forbidden lines of [O III] and [Ne III]. The present paper reports an attempt to further elucidate the nature of these objects using observations from the *IUE* satellite and additional high-dispersion ground-based data.

The new observational material is presented in § II. The next section discusses the implications for the stellar pair, while § IV discusses the planetary nebula. The final section contains a brief summary of the important conclusions. Throughout we assume the parameters for M22 ($D = 3100$ pc, $E(B-V) = 0.36$ mag, and low metallicity) adapted from the literature by Frogel, Cohen, and Persson (1983).

II. OBSERVATIONS

The *IUE* satellite was used to observe the spectrum of the *IRAS* source near the center of M22 for two low-radiation shifts in 1988 March and April. This is only the second PN known in a globular cluster; the first being K648 in M15, which has been studied with *IUE* by Adams *et al.* (1984). Because of the faintness of the object and the confusion of the crowded field, a double offset was used, first from a nearby SAO star to M22 V8, which could be seen by the visual guider camera (used for target acquisition), followed by a blind offset to the object. A total exposure time of 9.4 hr was accumulated in the short-wavelength camera in four separate images, and a total exposure of 5.5 hr was accumulated in three images of the long-wavelength camera. The object was surprisingly bright in the ultraviolet, and the individual LWP exposures were within 50% of the saturation level of the *IUE* detectors.

The echelle spectrograph built by S. Schectman of the Las Campanas Observatory near La Serena, Chile, was used on 1988 June 20 to observe the M22 PN with 1″.5 × 4 slit. The seeing was ~1″.5, and the night was clear. The slit was rotated to be perpendicular to the line joining the two stars. A 2 hr exposure was obtained of each component of the stellar pair. Notes taken while guiding indicate that the two stars were separated, but not as cleanly as was desired. Thirty minute exposures were taken of several brighter M22 stars near the *IRAS* source for comparison purposes. This fixed format echelle has a wavelength resolution of 4 pixels, with 0.083 Å per pixel at 5880 Å. A Th–A arc defined the wavelength scale.

The reduction of the echelle data was rather complex because the two-dimensional photon counting detector of Shectman, Price, and Thompson (1985) has severe spatial distortions. Using the Caltech image processing package FIGARO, the positions of the orders were fit by polynomials, the S-distortion was corrected, and the pixels across each order were summed. Thirty-seven orders were extracted, reaching from 3850 to 6593 Å. At the center of the echelle blaze, the final summed counts in any order never exceeded 300 counts per pixel (excluding emission lines).

III. LINE SPECTRUM OF THE PAIRS OF STARS

a) Echelle Spectra

The stellar pair consists of a very blue star (the southern component, hence we denote it hereafter as the S*) and a rather red one (the N*). The only absorption line present which is definitely ascribed to the N* is Hα, and its radial velocity is −32 km s^{-1}. Recall that the radial velocity of M22 is −153 km s^{-1} (Webbink 1981). The Hα profile shown in Figure 1 is deep and narrow, and is what would be expected for a field giant or supergiant. A star in the galactic bulge (recall that the galactic coordinates of M22 are $l = 9^\circ.9$, $b = -7^\circ.6$), with $M_V = -1.3$ mag would have a V magnitude comparable to

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[1] Guest Observer with the *International Ultraviolet Explorer Satellite*.

[2] Based in part on observations obtained at the Las Campanas Observatory of the Carnegie Institution of Washington as part of the agreement between California Institute of Technology and Carnegie Institution of Washington.

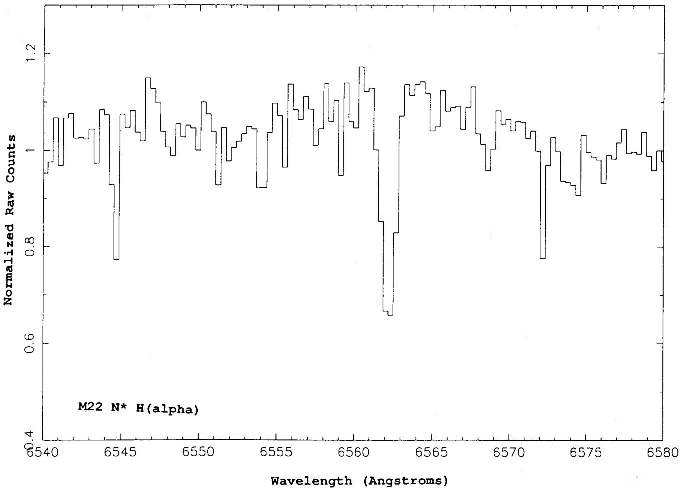

FIG. 1.—The normalized profile of Hα in the N* of the M22 *IRAS* source. It has been binned by a factor of 4 and slightly smoothed.

that of N* for $A_V = 1.5$ mag; the N* could thus be a low-metallicity K giant in the galactic bulge. The N* is probably not a member of M22.

The echelle spectrum of the S* is very different from that of the N*, so there was little contamination by the adjacent object. The spectrum of the S* shows lines of He II. All the lines are as shown in Figure 2 shallow and broad, typical of hot subdwarfs. The radial velocities are -148 km s^{-1} for the 6560 Å He II line, -147 km s^{-1} for 4686 Å He II line, and -154 km s^{-1} for the 4542 Å He II line. The S* is definitely a member of the globular cluster M22. The line at 6557 Å is broad, it is slightly perturbed by night sky Hα emission, and its centroid is not well measured, so the relative contribution of H to He cannot be accurately determined. However, based on the measured radial velocities, the dominant contribution to the line at 6557 Å is not Hα, but rather, the He II line of the Pickering series at 6560.10 Å. A reliable v_r cannot be measured from the Hβ line in the spectrum of the S*, as it too is broad, and is very close to the edge of an echelle order, where the continuum is dropping rapidly.

The ratio of strengths of the He II lines 4686–4542 and the absence of 4471 of He I indicates that the S* is hot, with $T_{\rm eff} \approx 55{,}000 \pm 10{,}000$ K. This estimate is based on comparison of the spectral features with those of stars analyzed by Mendez *et al.* (1988) using non–LTE model atmospheres. With better spectra and such a grid of non–LTE models, it should be possible to use the line profiles to determine the surface gravity, and He/H ratio in this star, as well as a more accurate value of $T_{\rm eff}$. We have not attempted to do so because the signal-to-noise (S/N) ratio of the present echelle spectra are inadequate. In addition, the true continuum level is uncertain to within at least 10% because of problems in the removal of the echelle blaze function, as well as possible low-level contamination by the N*.

b) *The IUE Spectra*

As a result of their spatial proximity, the individual contributions of the two components of the stellar pair cannot be separated by the *IUE* satellite. Examination of the original two-dimensional *IUE* data frames indicates that shortward of ~2500 Å, the spectrum is that of a point source and there was no substantial contribution from any other object. Above 2500 Å, one additional point source fell within the large *IUE* slit, but was substantially fainter than the N/S pair. The blind offset technique for locating the object within the large aperture was reasonably, but not completely, successful. The total flux in the four separate short-wavelength exposures ranged over a factor of 2, a similar range was seen for the three LWP exposures. The possible causes of such variation include the S* being a short-period variable, imperfect centering, or poor removal of the instrumental signature by the *IUE* data processing software. Whenever possible, exposures were taken in pairs, one with the SWP and one with the LWP, so as to minimize the overhead of target acquisition and camera preparation. There was no recentering (i.e., repeating of the blind offset) between the sequential exposures. We find that each pair of exposures is systematically either bright or faint. Thus, the most likely

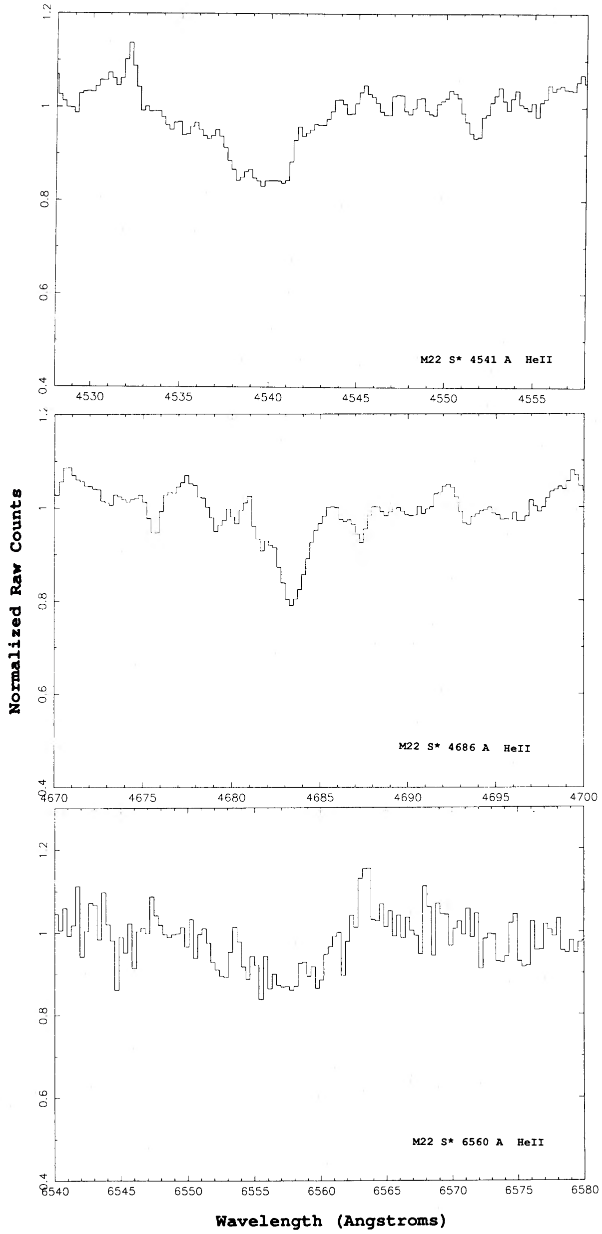

FIG. 2.—The normalized profiles of three of the He II features on the S*. They have been binned by a factor of 4 and slightly smoothed.

suspect is centering variations. A check of the pointing at the end of a LWP, SWP, LWP interchange revealed a definite accumulated pointing error of a few arcseconds, which *IUE* project staff described as normal behavior.

No emission features (from either a point source or the PN, which would appear slightly extended) were seen except for geocoronal Lyα. Two definite features (the line at 1549 Å of C IV and at 2800 Å of Mg II) and two probable ones (1335 Å of C II and 1656 Å of C I, perhaps with a contribution 1640 Å of He II) are present in absorption. As illustrated in the *IUE Spectral Atlas* (Wu *et al.* 1983) many O stars show such low ionization features. Based on the equivalent widths for interstellar lines in moderately reddened stars measured from *IUE* spectra by Joseph *et al.* (1986), we ascribe most of these features to interstellar lines, except for the C IV line. It is not possible to rule out a contribution from a stellar wind as well.

The C IV doublet (see Fig. 3) has a FWHM of 14 Å (2800 km s^{-1}), with $W_\lambda \approx 8$ Å. These values are quite similar to those observed by Adams *et al.* (1984) for K648 in M15, the only other known PN in a globular cluster. But the Lyα emission in the spectrum of the M22 PN, which is presumably mostly of geocoronal origin, has a FWHM of 2600 km s^{-1}. The instrumental line width is large, and may account completely for the observed C IV width. The velocity scale, which cannot be fully trusted, implies blueshifted absorption in the C IV doublet. There is no detectable sign of a stellar wind with a high-velocity flow, but better data at higher wavelength resolution would be desirable.

c) Interstellar Lines in Optical Spectra

Both components of the stellar pair, as well as the other stars observed in M22, show interstellar lines of Na I and Ca II. The lines are double, with v_r −14 and +28 km s^{-1}. Those in the echelle spectrum of the S* are shown in Figure 4. The spectrum of star M22 $V-15$ (in the nomenclature of Lloyd-Evans 1975) is shown for comparison, offset by 0.8 units vertically. There, one sees both interstellar components, as well as those of the star at v_r corresponding to that of the globular cluster M22. These are the same components as seen by Cohen (1981) in Na I at +29 and −6 km s^{-1}. Note that Cohen described the reddening to the cluster as spatially variable across the cluster. This has been confirmed by Crocker (1988). The Ca II/Na I ratio inferred from the interstellar lines is close to that expected for interstellar lines arising from typical path lengths through the galactic plane (excluding very dark clouds), and is about what is expected given the reddening to the globular cluster.

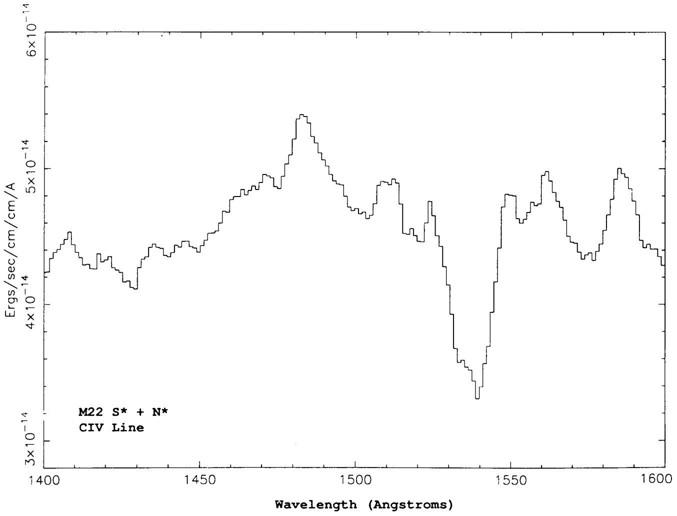

FIG. 3.—The smoothed profile of the C IV line in the M22 *IRAS* source from the *IUE* satellite observations. (The fluxes have not been corrected for interstellar absorption.)

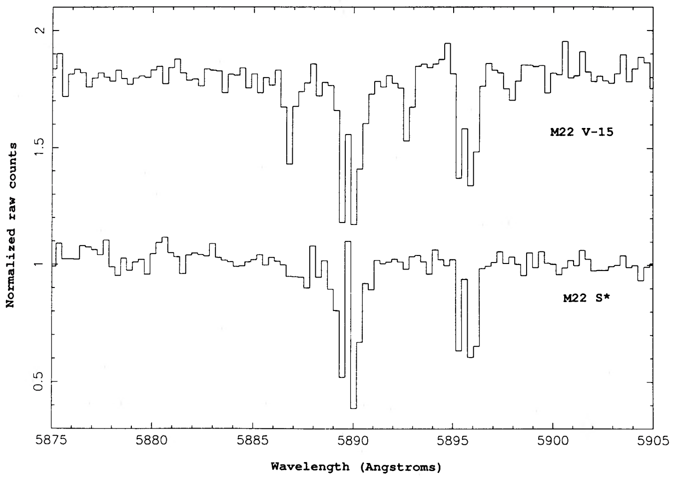

FIG. 4.—The region of the D lines of Na I in the spectrum of the S* and of the nearby giant M22 $V-15$. The spectra have been normalized, and are binned by a factor of 4 and slightly smoothed. The spectrum of the comparison star has been shifted vertically by 0.8 units.

The D lines in the spectrum of the N* show the same two components, so the N* is probably at least as far away as the globular cluster, but the lower velocity component of its interstellar D lines is in both members of the doublet somewhat stronger than those of the cluster stars. One does not expect much interstellar material behind the cluster along the line of sight, since M22 is ~410 pc below the galactic plane, so this could, in fact, be the stellar component of the D lines in a relatively low metallicity star, but one with v_r much closer to 0 km s^{-1} than to the v_r of the globular cluster.

IV. PLANETARY NEBULA AND STELLAR CONTINUUM DISTRIBUTION

a) Planetary Nebula

No additional emission lines are detected in these high-resolution echelle spectra beyond the four described in Gillett *et al.* (1989) that were seen in the earlier spectra from Palomar. In particular, there is still no sign of emission in any of the Balmer lines. The major peculiarity of the PN noted in the earlier preliminary study is thus unchanged. There are three similar objects known; Abell 30 and Abell 78 (Hazard *et al.* 1980; Jacoby and Ford 1983; Manchado, Pottasch, and Manpuso 1988; Harrington and Feibelman 1984) both have knots with no detectable Balmer line emission, although the outer parts of these two PNs show more normal ratios of hydrogen to metal emission lines. However, Greenstein and Minkowski (1964) found the central stars of A30 and A78 to both be Wolf-Rayet stars, with emission in O VI at 3811 and 3834 Å, and absorption in the C blend at 4650 Å, which exceeds that of He II at 4686 Å, properties quite different both at visual and ultraviolet wavelengths from those of the M22 S*. Although we expect the spectra of the central stars of A30 and A78 not to exhibit Balmer lines, the published spectra are of such a low dispersion that separation of the He II Pickering series from the H Balmer series is not possible and is further complicated by the overlapping of the much stronger nebular emission lines in these objects. Very recently, Boroson and Leibert (1988) have discovered one more such object, a nebula in the LMC (LMC 26) with a spectrum very similar to that of the M22 PN. A theoretical explanation for such objects involving a final thermal pulse after the central star of the PN has achieved a white dwarf configuration is given by Iben *et al.* (1983).

The radial velocity of the nebula is consistent with membership in M22, as expected. The emission lines of [O III] are resolved (although a fully double peaked profile is not seen); the expansion velocity of the nebula is 11 km s^{-1}. The radius of the nebula (for an apparent radius of 4″) is 0.06 pc, so that it fits nicely on the mean relationship between v_{exp} and size for galactic PNs reviewed and explained by Sabbadin *et al.* (1984).

Even in the *IUE* spectra, no emission lines were detected (with the exception of geocoronal Lyα). The individual raw frames were inspected carefully at Caltech and displayed at several stretches in an effort to locate nebular emission features. Because the interstellar reddening to M22 is large, the upper limits for the flux in the UV emission lines are fairly high. These may still be underestimates of the upper limits, because of the neglect of internal absorption within the rather dusty PN.

We can compare these upper limits for the M22 PN to those observed for K648 and for Abell 30. In the *IUE* spectra of the Abell 30 described by Harrington and Feibelman (1984), the strongest emission line is [C IV] 1549, and the extinction corrected ratio of [C IV]/5007 [O III] is 8. The upper limit for the M22 PN is 2. But the central star of A30 is extremely hot, with $T_{eff} \approx 200{,}000$ K (Greenstein 1981), although Kaler and Feibelman (1984) suggest that A30 is somewhat cooler. This is much hotter than we believe the temperature of the central star of the M22 PN to be. The *IUE* spectrum of A30 shows deep P Cygni absorption features. A comparison to K648 in M15 is perhaps more relevant. There Adams *et al.* (1984) found absorption rather than emission in [C IV] 1549. The strongest emission line they saw was [C III] 1908, with an extinction corrected flux ratio of [C III] 1908/[O III] 5007 of 3.1, which is above the upper limit of 1.0 for the M22 PN. But K648 has very high C abundance, while the M22 PN may not. Additional uncertainties affect these upper limits to the line ratios between UV emission lines and the optical [O III] lines. One relevant factor is the uncertainty in the total 5007 Å flux of the M22 PN to which Gillett *et al.* (1989) ascribe an uncertainty of a factor of 2. In addition, no correction has been made for mismatching of aperture size and centering with the *IUE* as compared to the optical data. The *IUE* large aperture has an effective size of 10″ × 20″. Given the size of the nebulosity, 10″ × 7″ (Gillett *et al.* 1989), the latter might also be large. Thus, we cannot ascribe great significnce to the apparently weaker UV emission lines in the M22 PN.

Greenstein (1981) has described the anomalous UV extinction of A30 and ascribed it to carbon smoke. The M22 PN may have a large internal extinction (which we have thus far ignored), and it may have a peculiar extinction law, but since the interstellar extinction itself is large, the disentangling of the various possible contributions to the total extinction is difficult. We should also note that the very strong IR flux which, when seen by the *IRAS* satellite led to the discovery of the M22 PN, is seen as well for A30 and A78, in the near-IR (Cohen *et al.* 1977). A30 is a very bright *IRAS* source with a spectrum very similar to that of M22 PN.

b) Stellar Continuum Flux

The continuum flux distribution for the central star of the M22 PN corrected for interstellar reddening using the extinction curve of Seaton (1979) shows a hot star. We use the model atmosphere fluxes of Kurucz (1979) for $T_{eff} \leq 40{,}000$ K, above which we approximate the spectral energy distribution by a blackbody. A fit of the extinction corrected UV and blue fluxes to that of a 50,000 K blackbody is shown in Figure 5. For the standard interstellar reddening to M22 of $E(B-V) = 0.36$ mag, T_{eff} is constrained to be 45,000 ± 10,000 K. This is in reasonable agreement with the requirements imposed by the ratio of the strength of the He II absorption lines, as well as the absence of He I absorption. However, $E(B-V)$ to the central star is probably somewhat larger than 0.36 mag because of reddening internal to the PN. In addition, there is the spatial variation in the interstellar reddening, which has an amplitude

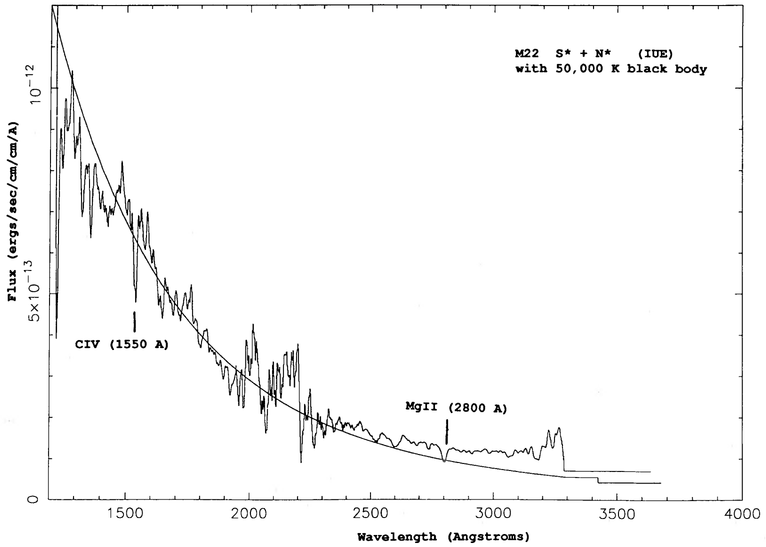

FIG. 5.—The smoothed *IUE* spectral energy distribution [corrected for $E(B-V) = 0.36$ mag] is compared to that from a 50,000 K blackbody

TABLE 1

PARAMETERS OF THE CENTRAL STAR OF THE PLANETARY NEBULA IN M22

$E(B-V)$	$T_{\rm eff}$	$\log (R/R_\odot)$	$\log (L/L_\odot)$
0.36 ……………	$45{,}000 \pm 10{,}000$	-0.34 ± 0.10	2.85 ± 0.10
0.50 ……………	$70{,}000 \pm 20{,}000$	-0.34 ± 0.10	3.64 ± 0.25
K648 …………	38,000	$+0.10$	3.48

of ~0.10 mag in $E(B-V)$. We therefore take as equally likely the value $E(B-V) = 0.50$ mag. The larger extinction implies a higher effective temperature, $T_{\rm eff} = 70{,}000 \pm 20{,}000$ K.

Since the distance to M22 is known, for a given absorption along the line of sight, we can calculate the radius and luminosity of the central star of the PN. The results are given in Table 1, where the values for K648 in M15 are from Adams *et al.* (1984). The luminosity of the red giant tip in M22 is 1900 $L_\odot$ (Frogel, Cohen, and Persson 1983), and is in reasonably good agreement with the luminosity derived for the S*.

Because of uncertainties in their distances, the validity of luminosity determinations for galactic PNs has always been dubious, and comparisons with theoretical evolutionary tracks have therefore been difficult. Evolutionary tracks have been calculated by Schönburner (1983) and by Wood and Faulkner (1986). A comparison with the observational data of Pottasch (1983) from the latter reference, indicated that the mean observed PN luminosities were low by about a factor of 3 as compared to the theoretical tracks. More recent luminosity determinations for CSPN by Mendez *et al.* (1988), based on high-dispersion spectra of the central stars, ignoring completely the nebular emission line fluxes, suggests that the observations and theory are now in better agreement, and that the distance scale derived by Pottasch was systematically too small.

We now have two PNs with good distances (because they are located in globular clusters) and relatively good determinations of the properties of their central stars via *IUE* observations. Our data provide independent high-quality evidence in support of theoretical tracks—the luminosities deduced for the two PNs with good distances are in good agreement with theory and with the red giant tip luminosity in globular clusters.

As one would expect, the mass of the central star determined from the evolutionary tracks for both the nebulae in globular clusters is low, between 0.60–0.55 $M_\odot$ (the theoretical lower limit for CSPN masses).

The dynamical time for expansion of the M22 PN (for a radius of 4″), given the $v_{\rm exp}$ we have measured of 11 km s^{-1}, is 5600 yr. This is quite comparable to the evolutionary time scale given by Wood and Faulkner (1986) provided that ejection of the PN occurs midway between the He shell flashes.

V. SUMMARY

The *IRAS* source near the center of the globular cluster M22 has been studied through spectra taken with the *IUE* satellite and with a high-dispersion echelle instrument at the Las Campanas Observatory. The optical counterpart is a close pair of stars, one of which (the N*) is not a member of M22. The S* is a member of the cluster, it is a hot star with $T_{\rm eff} \approx 50{,}000$ K, and it illuminates the PN. Both the PN and its central star show no evidence for Balmer lines in emission or absorption. All the stellar absorption features can be ascribed to He II. Thus both the PN and the central star are extremely H depleted.

The luminosity of the central star is in good agreement with that predicted by theoretical evolutionary tracks of post–AGB stars for a mass of ~0.57 $M_\odot$. It is comparable to the luminosity of the RGB tip in M22.

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REFERENCES

Adams, S., Seaton, M. J., Howard, I. D., Aurrere, M., and Walsh, J. R. 1984, *M.N.R.A.S.*, **207**, 471.
Boroson, T., and Liebert, J. 1988, preprint.
Cohen, J. G. 1981, *Ap. J.*, **247**, 869.
Cohen, M., Hudson, H. S., O'Dell, S. L., and Stein, W. A. 1977, *M.N.R.A.S.*, **181**, 233.
Crocker, D. A. 1988, *A.J.*, **96**, 1649.
Frogel, J. A., Cohen, J. G., and Persson, S. E. 1983, *Ap. J.*, **275**, 773.
Gillett, F. C., Jacoby, G. H., Joyce, R. R., Cohen, J. G., Neugebauer, G., Soifer, B. T., Nakajima, T., and Matthews, K. 1989, *Ap. J.*, **338**, 862.
Greenstein, J. L. 1981, *Ap. J.*, **245**, 124.
Greenstein, J. L., and Minkowski, R. 1964, *Ap. J.*, **140**, 1601.
Harrington, J. P., and Feibelman, W. A. 1984, *Ap. J.*, **27**, 716.
Hazard, C., Terlevich, R., Morton, D. C., Sargent, W. L. W., and Ferland, G. 1980, *Nature*, **285**, 463.
Iben, I. Jr., Kaler, J. B., Truran, J. W., and Renzini, A. 1983, *Ap. J.*, **264**, 605.
Jacoby, G. H., and Ford, H. S. 1983, *Ap. J.*, **266**, 298.
Joseph, C. L., Snow, T. P. Jr., Seab, C. G., and Cruther, R. 1986, *Ap. J.*, **309**, 771.
Kaler, J. B., and Feibelman, W. A. 1984, *Ap. J.*, **282**, 719.
Kurucz, R. L. 1979, *Ap. J. Suppl.*, **40**, 1.
Lloyd-Evans, T. 1975, *M.N.R.A.S.*, **171**, 647.
Manchado, A., Pottasch, S. R., and Manpuso, A. 1988, *Astr. Ap.*, **191**, 128.
Mendez, R. H., Kudritzski, R. P., Herrero, A., Husfield, D., and Groth, H. G. 1988, *Astr. Ap.*, **190**, 113.
Pottasch, S. R. 1983, in *IAU Symposium 103, Planetary Nebulae*, ed. D. R. Flower (Dordrecht: Reidel), p. 391.
Sabbadin, F., Gratton, R. G., Bianchini, A., and Ortolani, S. 1984, *Astr. Ap.*, **136**, 181.
Schönberner, D. 1983, *Ap. J.*, **272**, 708.
Seaton, M. J. 1979, *M.N.R.A.S.*, **187**, 73P.
Schectman, S. A., Price, C., and Thompson, I. B. 1985, Annual Report of the Director (Washington: Mount Wilson and Las Campanas Observatories, 1984–1985), p. 52.
Webbink, R. F. 1981, *Ap. J. Suppl.*, **45**, 259.
Wood, P. R., and Faulkner, D. J. 1986, *Ap. J.*, **307**, 659.
Wu, X. X., *et al.* 1983, *The I.U.E. Ultraviolet Spectral Atlas, IUE NASA Newsletter*, No. 22.

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