THE DISTANCE SCALE OF PLANETARY NEBULAE

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The spectacular success of the so-called Shklovsky method of finding distances to planetary nebulae which are optically thin to the Lyman continuum (Shklovsky 1956; see also Minkowski and Aller 1954) has produced within us a rather breath-taking boldness. Following the careful application of this method to more than 600 planetaries by Cahn and Kaler (1971), we now have the audacity to use planetaries as reliable distance indicators to derive an improved model of our own galaxy (Cahn 1976), trace the evolution of stars in their post-giant stages (O'Dell 1974, Cahn and Wyatt 1976), and even determine distances to other stellar systems (Ford, Jenner, and Epps 1973). At the Tatranská Lomnica meeting 10 years ago, there seemed little hope that one day soon planetary nebulae distances would become reliable. That day is near if not here already.

But these heady applications of planetary nebulae also bring to us the weighty responsibility of correctly establishing the distance scale. As expressed by Seaton (1968), and re-stated by Cahn and Kaler, the fundamental formula is $R = KS^{-1/5}$ where R is the radius of a nebula optically thin to the Lyman continuum, and S is the directly observable surface brightness. The proportionality coefficient

$$K \propto M^{2/5} \varepsilon^{-1/5} f[y, \alpha(H\beta)]$$

where $\alpha(H\beta)$ = effective Hβ recombination coefficient, $y = N(He)/N(H)$, ε = filling factor (fraction of sphere filled with radiating matter), and M = mass of nebula. The basic goal is to evaluate the quantity K, if not for each individual nebula, then as an average value for all planetaries. $f[y,\alpha]$ has a relatively small range, and use of a mean value appears to be acceptable. Besides having a small exponent, ε can be roughly determined for many nebulae by inspection of Hβ images and is usually assumed to be ~ 0.6. Mass is the important factor. If we were to decide, for example, that a certain nebula has a mass between 0.05 and 1.0 $M_\odot$, then possible distances will range over a factor of 3.3. Clearly, our efforts

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must be concentrated on evaluation of M.

Basically, to find the total mass, M, one derives it experimentally by using planetaries for which reliable distances are otherwise available and solving the fundamental formula for M. Mean values of the mass have been calculated by a number of investigators including Minkowski and Aller (1954), Shklovsky (1956), Kohoutek (1961), O'Dell (1962), Perek (1963), Minkowski (1965a,b), Seaton (1966, 1968), Abell (1966), Webster (1969, 1976), Cudworth (1974), and Perinotto (1975). Happily the various values adopted have a modest range, namely 0.14 to 0.47 $M_{\odot}$ which corresponds to a range in distance determinations of 1.62 times.

The values of M that have been adopted in recent years usually fall between 0.14 and 0.18 $M_{\odot}$ stemming from the results of O'Dell (1962) and Seaton (1968). The 1968 Seaton scale weighs most heavily on Webster's (1969) calibration of Magellanic Cloud planetaries. More specifically, Seaton assumed that the brightest nebulae in the Magellanic Clouds were similar to the brightest galactic planetary nebulae, an assumption that Webster (1975) noted was only partially valid since both compositions and degrees of excitation appear to differ in the three galaxies. It is not entirely clear how these differences will affect the calibration; clearly more work is vitally needed.

At the high end of the mass range we have the recent study by Cudworth (1974) of proper motions and statistical parallaxes. His results for optically thin planetaries differ strikingly from those of Cahn and Kaler and instead agree almost exactly with Seaton's (1966) earlier scale. For proper motion work, it is necessary to have moderately low nebular surface brightnesses and reasonably bright central stars. Possibly these selection requirements conspire to give nebular masses which are substantially above average; however, there is no *a priori* reason to believe so. Perhaps the explanation of the discrepancy lies in the method: the sub-system of planetary nebulae, generally believed to be an old disk population, may for some reason have velocities unsuitable for use in statistical parallax studies.

When we plot the distances derived by Cudworth against those of Cahn and Kaler, we find a most illuminating relationship: the optically thin planetaries define well a straight line relationship between the two scales. Because much of the basic data (surface brightnesses and interstellar extinction) come from the same source, the scatter would be expected to be small. More significant is the slope of the line (0.63) which gives directly the ratio of the two distance scales. These remarks, it should be emphasized, apply only to optically thin nebulae which show a scatter about the best straight line of $\sim$ 7 percent.

For optically thick planetaries the agreement between Cahn

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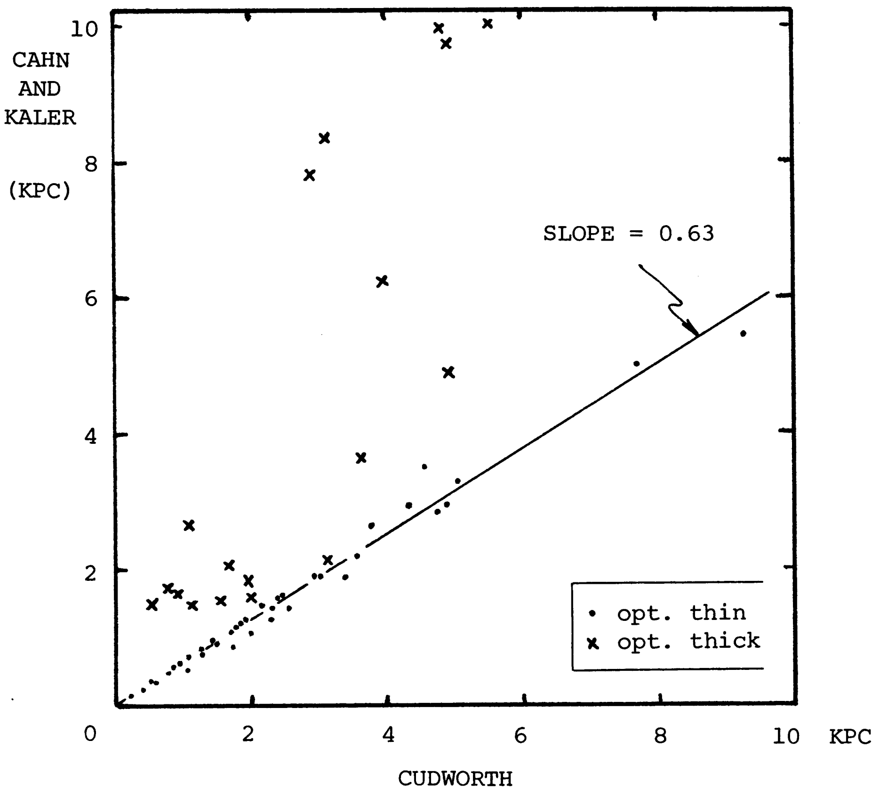

Figure 1

and Kaler and Cudworth is poor. Basically, the reason is that Cahn and Kaler treat the two types of planetaries in a like manner and note in their paper that since not all the gas in an optically thick nebula radiates, the distances are upper limits. Cudworth uses the method of constant absolute magnitude for thick nebulae (see Minkowski 1965b) and derives a distance scale which agrees well with that of Minkowski. To decide if a nebula is thick or thin, Cahn and Kaler adopt the relationship 0.08 pc $< R <$ 0.4 pc as the criterion for when a planetary is optically thin. (Cudworth takes 0.07 pc as the lower bound.)

Cahn and Kaler clearly state that their distances for optically thick nebulae are to be taken as upper limits. From the distribution of points in Figure 1, it should be concluded that this warning cannot be stressed too heavily.

In a paper evaluating various distance scales with the expanding shell technique (see below), H. Smith (1971) confirmed that distances to optically thick nebulae, as measured by the Shklovsky method, were too great and that the distance values given

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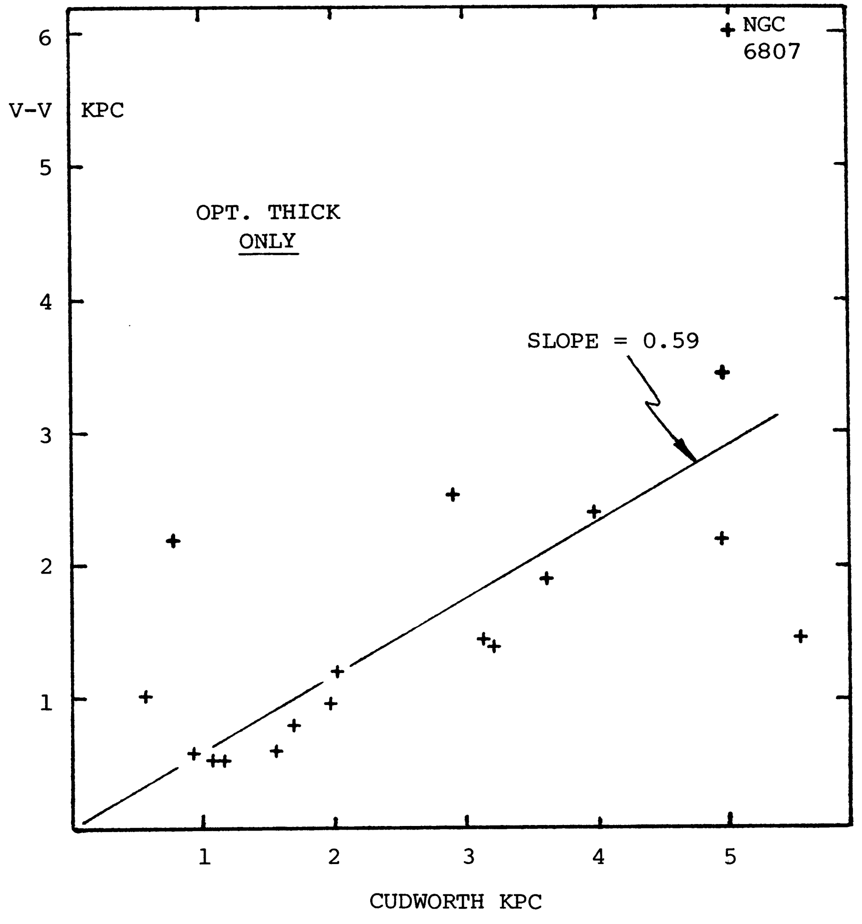

Figure 2

by Vorontsov-Velyaminov (1950) were to be greatly preferred. The method employed by Vorontsov-Velyaminov uses the size of the ionized hydrogen region as the standard, a technique which can be traced back to Zanstra (1931). Figure 2, which includes only optically thick planetaries, shows the somewhat closer agreement between the distances of Vorontsov-Velyaminov and of Cudworth. With an adjustment of distance scales, the agreement averages approximately ± 12%. It is hoped that soon the tabulation of Vorontsov-Velyaminov will be re-done using modern observed quantities.

Smith, using shell expansion velocities for the comparison, evaluated several distance scales. In principle, the technique is straightforward: one compares nebular expansion velocities as measured spectroscopically (evidenced by the splitting of emission lines) with the angular expansions derived by comparing the location of knots, filaments, edges, and other features seen on both old and new photographs. If spherical symmetry obtains, then the calculation of distance is straightforward. Angular expansion rates have been determined by a number of investigators including Latypov (1955), Chudovicheva (1964), Liller (1965), Liller *et al.* (1966) and Liller and Liller (1968). Radial velocity measurements have been made primarily by Wilson (1950, 1964). The problems become increasingly numerous as one considers the details, partly because of non-uniform plate material and partly because of the difficulty of finding sharply defined features to measure. On the whole, however, the errors should be mainly random and correction factors to various distance scales can be established.

Can expansion measurements allow us to choose between the conflicting distance scales of Cudworth and Cahn and Kaler? Fig. 3 shows the best fit straight lines for optically thin nebulae comparing the distances derived from shell expansions (all from Liller and colleagues) with (a) Cudworth and (b) the Cahn-Kaler distances. The slopes of the best fits are 0.48 and 0.85 respectively, suggesting that the Cahn-Kaler scale is more nearly correct. However, the points divide into two groups, each strongly correlated with galactic latitude. In the Cahn-Kaler comparison, Fig. 3b, the

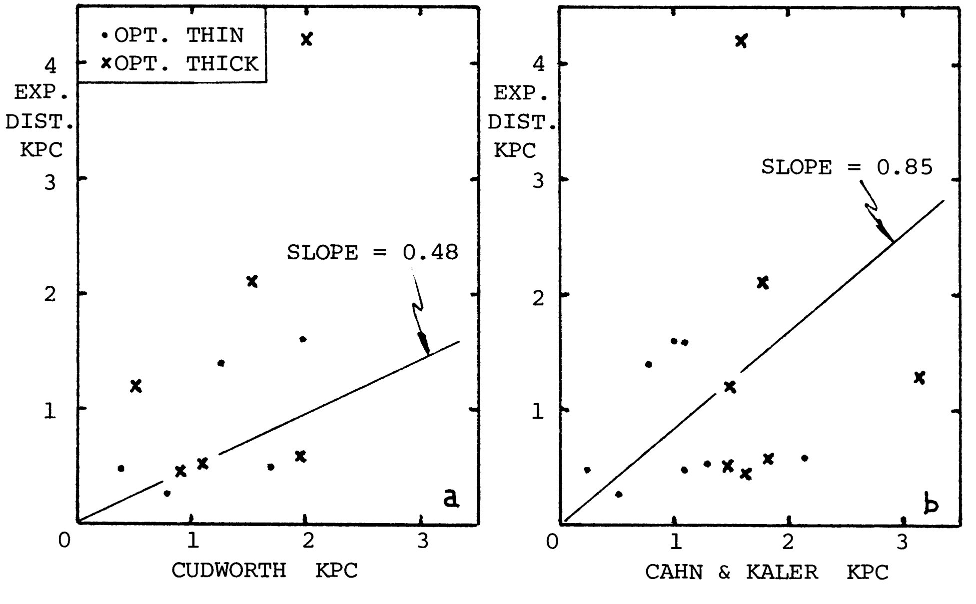

Figure 3 a,b

average absolute value of b^{II} for points above the line is 9°.3 while for points below the line b^{II} averages 34°. All four planetaries above the line have $b^{II} < 18°$, and below the line, except for one object (NGC 7009), all have $b^{II} > 31°$. It would seem as if the interstellar medium or low latitude magnetic fields have produced apparent features and condensations which move outward slowly (or not at all) giving us misleading results. This possibility has, in fact, been raised before (Liller, *et al.* 1966).

The separation of points into galactic latitude groups is not seen at all clearly with the optically thick nebulae which is perhaps not surprising if the interstellar medium or magnetic fields are involved. However, it is clear that for optically thin nebulae we must view the distances derived with the expanding shell technique with suspicion.

It should be noted that Cahn and Kaler are continuing to revise their results. At last reading (Cahn 1976), their judgement was that on the average their distances should be increased by 5-10 percent.

Other methods have been used to measure distances to planetary nebulae which can provide scale checks. Lutz (1973) compared color excesses and estimated distances of normal stars in the direction of 6 planetaries for which color excesses were available. Comparison of her distances with those of Cudworth and Cahn and Kaler does not provide enough information for a clear choice, but the technique has been proven sound and should be applied to many additional nebulae. While individual distance determinations may not be of the highest quality, there should be a few systematic effects and the result of applying this technique to a much larger number of planetaries would be of tremendous importance.

Several people (see, e.g. Bohuski and Smith 1974) have pointed out that a relationship exists between the size of a planetary nebula and the expansion velocity. If it becomes possible to put this relationship on a quantitative basis, it should prove useful to calibrate distance scales.

A recent private communication from Sackmann and Trimble describes a new technique for calibrating the distance scale of planetaries. Their basic assumption is that nebulae are expelled in helium shell flashes, and if these flashes occur at fixed time intervals, multiple shell planetaries should yield reliable distances. Their results will be of much interest.

Lastly, we can base the distance scale on individual planetaries which for some reason or other have a special quality making it possible to derive a distance. Given a moderate number of such objects, they can serve as calibrators of more general distance

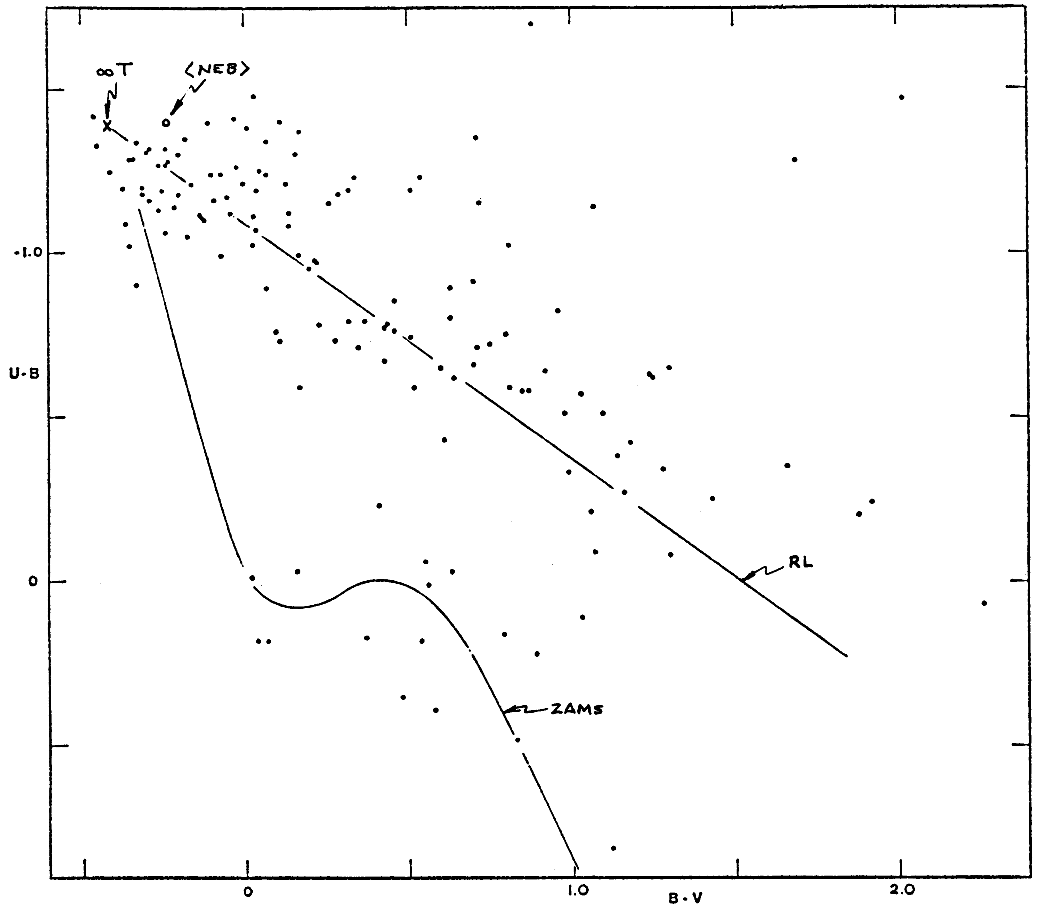

Figure 4

determination methods.

Listed below are some of these special planetary nebulae:

Central stars with physical companions:

NGC 246. 4" distant is a G8-K0 main sequence star with which Minkowski (1959) derived a spectroscopic parallax of 430 parsecs.

NGC 6853, Abell 24, Abell 33. According to Cudworth (1973) all three have optical companions. Spectroscopic studies would be most valuable.

Planetaries with "normal" unresolved companions: Shao and Liller (1968) have measured UBV colors of 149 central stars, and while most are appropriate to high temperature stars reddened to a certain degree by the interstellar medium, 17 appear to have colors more similar to ordinary main sequence stars. See Fig. 4.

Table 1

Planetary nebulae with unusually colored central stars (ultraviolet deficiencies)

P-K	Other	B-V	U-B
235+ 1°1	V-V 1-7	+0.04	+0.18
272+12°1	NGC 3132 + HD 87892	+0.07	+0.18
321-16°1	He 2-185	+0.54	+0.18
324 - 1°1	He 2-133 = HD 139636 (Sp. A0)	+0.16	-0.03
330 + 4°1	Cn 1-1	+0.83	+0.48
1 - 0°1	Bl 3-11 = HD 316290 (Sp. = F8)	+0.56	+0.01
2 + 1°1	H 2-20	+0.58	+0.39
45+24°1	K 1-14	+0.63	-0.03
59 - 1°1	He 1-3	+0.37	+0.17
60 - 7°1	He 1-5	+0.48	+0.36
61 + 8°1	K 3-27	+0.79	+0.16
63-12°1	He 2-467	+0.41	-0.23
96 + 2°1	K 3-61	+1.12	+0.81
118 - 8°1	Vy 1-1	+0.02	-0.01
133 - 8°1	M 1-2 = VV 8	+1.03	+0.24
165-15°1	NGC 1514	+0.55	-0.06
169 - 0°1	IC 2120	+0.91	+0.18

Clearly, we are seeing the brighter companion of an unresolved binary with the fainter star (optically) being the high temperature nucleus. These objects are listed in Table 1 and all deserve further study. Three have already received attention:

NGC 1514. Kohoutek (1970) has carefully studied the spectrum of the central stars and has derived a distance of 480 parsecs.

NGC 3132. Méndez (1975), from a study of the spectrum, arrives at a distance of 479 parsecs.

NGC 1360. A spectroscopic binary, according to Méndez and Niemela (1977), but in the photographic region, the hot star dominates. Infra-red observations should give valuable information.

Two planetaries of special interest:

FG Sagittae. A remarkable variable star which now appears to be the central star of a bonafide planetary nebula. According to Flannery and Herbig (1973), its distance is 2.5 kpc.

UU Sagittae = Abell 63. Bond (1976) noted that the central star of Abell 63 was identical to the variable UU Sge. According to Miller *et al.* (1976) its period is ∿ 11 hours with a primary eclipse lasting less than an hour. Depth of eclipse is more than 4 mag. Further study of this star should provide us with much valuable information, including limits on the distance.

Finally, as many as three planetaries may be physically associated with globular clusters and thus have reliable distances:

K 348 in M15. Discovered by Pease (1928) and well-studied. Distance = 10.1 kpc (Harris 1976).

In M15. At the center, there may be a very faint planetary, according to Peterson (1976). It is possibly associated with the X-ray source believed to be at the cluster center.

In NGC 6401. Peterson (1977) has found a planetary ∿ 3' away from this globular cluster. The nebula and cluster are possibly physically associated.

In conclusion, it seems obvious that at least for optically thin nebulae, it is potentially possible to derive accurate distances (± 10%). All that is needed is a careful calibration of the scale. At the present time we do not have such a calibration but several should be possible. Until the better calibrations are made, the recommendations of this reviewer are:

1) For optically thin nebulae, use the distances of Cahn and Kaler (1971) increased by 10 percent -- or communicate with Cahn or Kaler directly for their latest unpublished values. Their techniques are sound and their survey large, and until further indication that this distance scale is clearly too small, their distances should be given highest weight.

2) For optically thick nebulae, use the distances of Vorontsov-Velyaminov (1950) increased by about 25 percent, a judicious estimate based on the findings of Smith (1971) and on Cudworth's (1974) results.

Specifically, it is recommended that (1) the color-vs-distance survey of Lutz be extended to a much larger number of objects. While individual errors may be sizeable, systematic errors should be small, and the number of possible objects that can be studied is large. (2) Detailed spectroscopic studies should be undertaken to learn more about the "normal" companion stars of the planetary nuclei listed in Table 1.

(3) Finally, and perhaps most importantly, we should return to the Magellanic Clouds. It is tremendously important to study the planetaries there with the new large telescopes in the Southern Hemisphere and refine the pioneering work of Webster. After all, the Magellanic Clouds played a major role in calibrating the Cepheid variable distance scale; now they should be used to put planetary nebulae, the newest of the distance indicators, on a firm footing.

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DISCUSSION

Bonilha: How do you distinguish optically thin and optically thick planetary nebulae? The original criterion used by Seaton involved the presence of [OI] lines to indicate thickness, but it is known now that most planetary nebulae have neutral condensations.
Liller: The criterion that Cahn and Kaler used was just the size. The feeling was that in the evolution of the planetary early in its history it is small and very dense and its outer regions cannot get ionizing radiation. Later when it's very large, there is no radiation adequate to get to that far a distance.
Seaton: I do not think that the presence of [OI] can be used to determine that a nebula is optically thick. The [OI] could come from deeply embedded knots in an optically thin nebula.
Heap: I would like to suggest another method for a distance scale - the method of spectroscopic parallax. One way of getting the luminosity of a central star is through calibration of young O stars. The reasoning goes like this. From Stephan's Law the luminosity is proportional to the radius squared and the temperature to the fourth power. If you substitute for the radius, it goes as the mass, temperature to the fourth power, and the gravity. For stars of the same spectral type, the temperature and the gravity are the same. So the visual luminosity to mass ratio of a planetary nucleus with an O type spectrum identical to a young O star would be the same as the luminosity to mass ratio of a young star. Suppose we took a mass ratio of young star to central star of 60, which is high, and derive what the distances to planetary nuclei having O type spectra are. In those cases, I find distances 80% greater than Cahn and Kaler's, but only about 20% greater than Cudworth's. To get these distances down to Cahn and Kaler's distances, you would have to say the mass ratios of young stars to planetary nuclei were 200 or more; or you would have to say the photometry of central stars is systematically 1.3 magnitudes off, both of which seem unreasonable. The method of spectroscopic parallax tends to support the Cudworth distance scale.