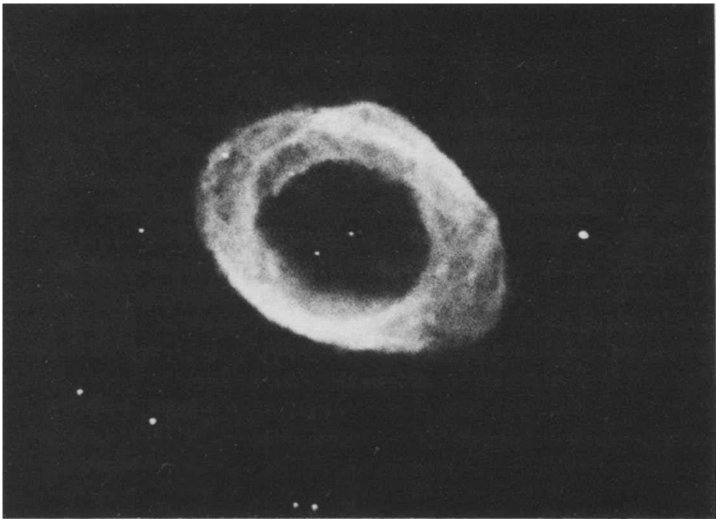

NGC 6720

SESSION I

THE DISTRIBUTION OF PLANETARY NEBULAE

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STATISTICS -- SPATIAL AND VELOCITY DISTRIBUTION OF PLANETARY NEBULAE

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1. INTRODUCTION

The problems of the spatial and velocity distributions of planetary nebulae in our galaxy are still very much with us. In what follows we comment rather hastily on the older work and more especially on the recent work in these fields. We have not been able to carry out an exhaustive literature search, and therefore trust we shall be forgiven by those whose contributions do not appear herein. We first survey the scene in the greater solar neighborhood. Section 2 deals with the local spatial distribution of planetaries in the galactic plane and perpendicular to the plane. Section 3 focuses on the rather meager results that can be obtained on the kinematical properties of the planetaries in our general part of the galactic system. We conclude by moving farther afield and exploring another part of the galaxy and the galaxy as a whole. Section 4 addresses the distribution of planetaries and summarizes recent estimates of the total planetary population of our galaxy. Finally, Section 5 is devoted to what little one can conclude about the overall kinematical properties of the system of planetaries.

2. SPATIAL DISTRIBUTION IN THE SOLAR NEIGHBORHOOD

We first comment on the statistics of the solar neighborhood. Concerning the local number density of planetary nebulae, we note that Cahn and Kaler (1971) estimated $n_o \sim 50$ kpc^{-3}, based on the Seaton (1968) distance scale. This figure refers to optically thin systems, which constitute the great majority of all detectable planetaries. More recently, Cahn and Wyatt (1976) found $n_o \sim 80$ kpc^{-3}, in essential agreement with Cahn and Kaler (1971), except that they corrected for a deficiency in the discovery of southern planetaries of low surface brightness. Their estimate was also founded on the Seaton distance scale; transformation to the Cudworth (1974) scale has the effect of reducing their figure by a factor of about $1.4^3 = 2.7$ to $n_o \sim 30$ kpc^{-3}. Whatever the "ultimate" value may be, it appears that one star out of every 1 - 3 million is now surrounded by a detectable planetary.

Yervant Terzian (ed.), Planetary Nebulae, Observations and Theory, 3-9.

Salpeter (1971) suggested that the local birthrate and deathrate of planetary nebulae is in reasonable agreement with the deathrate of main-sequence stars and the birthrate of white dwarfs. Cahn and Wyatt (1976) found, for typical planetary lifetimes, that the local birth-rate and deathrate is in the range 4 - 6 x 10^{-3} kpc^{-3} yr^{-1} for the "short" distance scale, or about 1.5 - 2 x 10^{-3} kpc^{-3} yr^{-1} for the "long" scale. These rates are to be compared with 2-3 x 10^{-3} kpc^{-3} yr^{-1} (Cahn and Wyatt 1976) for the local deathrate of main-sequence stars over the relevant mass range (about 1 - 4 solar masses) and 2 - 5 x 10^{-3} kpc^{-3} yr^{-1} (Weidemann 1968) for the local birthrate of white dwarfs. There are inevitable uncertainties in these estimates, probably up to a factor of two or three. And they may require modification as fresh observations and theoretical developments become available. For now, we stress that the rates given above are too uncertain to allow assessment of the appropriate distance scale for planetary nebulae.

The distribution of planetaries perpendicular to the galactic plane yields a relatively small scale height. Cahn and Kaler (1971) found a scale height in z of ~ 90 pc; Alloin, Cruz-Gonzalez, and Peimbert (1975) estimated ~ 160 pc; and Cahn and Wyatt (1976) deduced ~ 115 pc. These values are greater than those usually ascribed to the young main-sequence stars and interstellar matter, but substantially smaller than those ascribed to the "common" rather elderly stars. The essential reason, of course, is that our present population of planetaries originates in stars having a variety of main-sequence masses and therefore main-sequence lifetimes. On the basis of the stellar deathrate function described in Cahn and Wyatt (1976) we have calculated the expected distribution function, n(z), for planetaries from established information about their predecessors. These calculations employ data on the velocity dispersion perpendicular to the galactic plane of main-sequence stars of different spectral class (and therefore mass) (Delhaye 1965), and they also employ the acceleration function, K(z), deduced by Oort (1960). The deduced n(z) at each main-sequence mass can then be checked against published values. The results are then weighted by the deathrate function to yield a predicted n(z) for planetaries. The decreasing trend of number density with distance from the plane accords rather nicely with the data on planetary nebulae and is consistent with current ideas about the parentage of the planetaries. Preliminarily, the estimated scale height of the progenitor stars appears to lie in the range of 100 - 150 pc, which is in broad agreement with evaluations of the planetary scale height as cited above. Unfortunately, however, the progenitor scale height has an uncertainty of perhaps a factor ~ 1.5, so that this approach cannot be used with confidence at the present time to decide on a "proper" distance scale for the planetary nebulae.

It would, of course, be most interesting to check the distribution of perpendicular velocities of planetaries directly against those of their supposed progenitor stars. The difficulties of this kind of analysis are formidable, however. Reliable radial velocities yield good perpendicular velocities only for planetaries close to the galactic poles, and there is only a handful of such objects, as found from the Perek and Kohoutek catalog (1967) and more recent sources. Proper motions relative to the background frame of galaxies are full of promise for evaluating transverse velocities, but to date the time baselines are rather limited and the quoted mean errors (Cudworth 1974) continue to be moderately large.

3. KINEMATICAL PROPERTIES IN THE SOLAR NEIGHBORHOOD

The main clues to the velocity distribution of planetaries must, at the present time, be sought in analyses of the radial velocities. The essential finding for the local distribution goes back as far as the work of Wirtz (1922), who found that the group motion of the planetaries along the Cygnus velocity axis (ℓ = 90°, b = 0°) is $\sim$ -30 km s^{-1} relative to the sun. In terms of galactic rotation, this figure implies a lag of 15 - 20 km s^{-1} with respect to circular velocity. A recent example is provided by the analysis of Cudworth (1974), whose findings imply a lag of 10 km s^{-1}. We obtain comparable results when we survey the 31 planetaries within the two 40° by 40° rectangles centered on ℓ = 90°, b = 0° and ℓ = 270°, b = 0°, for which both radial velocities and appropriate astrophysical distances are available. With the help of the Schmidt model (1965), we calculate the radial component of the circular velocity at the location of each planetary relative to our local standard of rest. We then compare this value with the observed radial velocity reduced to the local standard of rest. The mean 0 - C is $\sim$ - 10 km s^{-1} and the median 0 - C is $\sim$ - 20 km s^{-1}. These various estimates do not appear to be inconsistent with the known kinematical properties of main-sequence progenitor stars in the mass range $\sim$ 1 - 4 $M_\odot$. The summary by Delhaye (1965) indicates that the lag behind circular velocity ranges from about zero for main-sequence stars near spectral class AO to some -10 to -20 km s^{-1} near class GO. For both "nearby" planetaries and main-sequence stars of modest mass we appear to be sampling objects that on the average are moving in somewhat eccentric galactic orbits and most of whose semimajor axes are smaller than the sun's distance from the galactic center.

When we turn to the statistics of velocities perpendicular to the galactic plane, the data at hand are not at all revealing. As has already been mentioned, in order to assess the perpendicular speed of any object from its radial velocity alone, we must confine our sampling to a small fraction of the sky within, say, 20° or 30° of the galactic poles. Of all the planetaries in the Perek-Kohoutek catalog (1967) with measured radial velocities, only three lie within 30° of the galactic poles. Therefore we pursue this question no further.

4. THE GALACTIC DISTRIBUTION OF PLANETARIES

The data on planetaries in the greater solar neighborhood (Cahn and Wyatt, 1976) makes it possible to construct a luminosity function for these planetaries. The resulting function is reasonably complete for H_β luminosities over the range 0.1 to 10 times the integrated luminosity of the sun. We have examined an unpublished 1975 version of the Cahn and Kaler (1971) catalog of planetary nebulae in the direction of the galactic center over a rectangle of 20° by 20°. Between 5 and 6 kpc we find enough planetaries of high luminosity to match the upper end of the local luminosity function and therefore to estimate the density amplification. We find that the column density of planetaries 5 to 6 kpc from the sun toward the galactic center is about 4 times the local column density. This compares well with the B surface brightness of M31 (de Vaucouleurs, 1958), which is 4½ times brighter 1/3 of the way out along the major axis than it is 2/3 of the way out. Also, Schmidt's (1965) model of the galaxy implies that the ratio of density between that at 5 and 10 kpc from the galactic center is 4.6. Still another piece of evidence is the mass model of Einasto and Rümmel (1970), for which a radial scale factor of 5 kpc is deduced on the assumption of an exponential density decay. Our ratio of column densities of 4 implies a radial scale factor of $\sim$ 4 kpc, not very different from those quoted above.

The newly derived scale factor makes it possible to make a new estimate of the total number of planetaries in the galaxy. Cahn and Kaler (1971) made use of Perek's (1962) density distribution

$$n = n_c \exp(-m),$$

where $m^2 = (R/a)^2 + (z/c)^2$ and n_c is the central density, to define the variation of density with the cylindrical coordinates R and z. The corresponding scale factors are a and c. As Perek (1962) showed, the total number in the galaxy is simply

$$N = 8\pi a^2 c\, n_c \,.$$

Cahn and Kaler then tried to determine a, c, and n_c from data in the solar neighborhood, with somewhat spectacular results. Their radial scale distance of a = 1.4 kpc led to a central density of

$$n_c = 50 \exp(10/1.4) \sim 63{,}000 \text{ kpc}^{-3}$$

and about half a million planetaries in the galaxy as a whole. Subsequent experience has shown that the radial gradient of planetaries across the greater solar neighborhood is too small to determine reliably. The new radial scale factor of a = 4 kpc deduced above leads to a more reasonable central density of $\sim$ 1000 kpc^{-3} if we adopt Cahn and Wyatt's (1976) local density. The total number of planetaries in the galaxy is then 45,000 if we adopt their scale height of 0.115 kpc.

Several other estimates of the total galactic population of planetaries have been made recently. Alloin, Cruz-Gonzalez, and Peimbert (1976) estimated a total of 6000 - 30,000, while Cahn and Wyatt (1976) found a value of 38,000 ± 12,000. It should be recalled that the latter investigation is tied to the Seaton (1968) distance scale. Use of Cudworth's (1974) distance scale reduces the total by a factor of $\sim$ 3.

Independent evidence may be sought through investigations of external galaxies similar to our own. Such studies are of very recent origin, and are currently confined to one system. Ford and Jacoby (1977) have amplified the list of known planetaries in M31 by a factor of ~ 60 through analysis of their on-line and off-line photographs at wavelengths at and near λ5007 [OIII]. Their extrapolation from well-chosen sample areas to the entire spiral suggests that M31 contains $\sim$2700 planetaries within three magnitudes of the most luminous ones. As mentioned above, we have examined the luminosity function of planetaries in the greater solar neighborhood (Wyatt and Cahn 1977) and find that 5 - 10 percent of all planetaries to our limit of completeness (radius $\sim$ 0.50 pc) are young enough and luminous enough to rank in the brightest three magnitudes. We thus conclude from the work of Ford and Jacoby that M31 contains $\sim$ 27,000 - 54,000 planetaries comparable to those that are included in the statistics of the solar neighborhood. If M31 is assumed to be twice as massive as our own galaxy, we may indirectly judge that the total galactic population is $\sim$ 13,500 - 27,000, a range of values that overlaps and is intermediate between those of Alloin, Cruz-Gonzalez, and Peimbert (1975) and Cahn and Wyatt (1976), and somewhat less than our estimate in the preceding paragraph.

If we couple all four population estimates to the Seaton distance scale and to a mean observable lifetime of $\tau_{PN} \sim 0.50$ pc/20 km s^{-1} $\sim$ 25,000 yr, it follows that the galactic birthrate and deathrate of planetary nebulae in our times is in the range 1 - 2 yr^{-1}. On the Cudworth scale these rates are reduced to 0.3 - 0.7 yr^{-1}. This range of values is in reasonable accord with those for the deathrate of stars with main-sequence masses in the range 1 - 4 solar masses (Cahn and Wyatt 1976) and the birthrate of white dwarfs (Weidemann 1968), suggesting that all stars within this range of main-sequence masses eject planetary nebulae on their trips to the realm of the white dwarfs. The uncertainty in the estimated rates remains large enough, however, to accomodate other possibilities. We mention only two. First, the lower limit of main-sequence mass for stars that undergo planetary ejection may be 1.2 - 1.3 solar masses, as suggested by Wood and Cahn (1977), instead of 1.0 as assumed by Cahn and Wyatt (1976). Second, the upper limit of main-sequence mass for stars that undergo planetary ejection continues to be somewhat uncertain, although future readjustments to this limit will not have much effect because such massive stars are relatively rare per unit volume of space. Although these possibilities may prove of some significance in future studies, we surmise for now that comparisons of the statistics of planetary birthrates and deathrates with those of main-sequence deathrates and white dwarf birthrates will not need alteration by more than half an order of magnitude.

5. THE GALACTIC VELOCITY DISTRIBUTION

Some years ago Minkowski (1965) and Perek (1968) reviewed the velocity data on planetaries and their interpretation. Of particular note are their summarizing plots of radial velocities against galactic longitude. Data at a variety of longitudes defy the hypothesis of circular motion for the planetary nebulae as a group. The most striking

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part of the Minkowski and Perek diagrams is the region very near the galactic center; in that part of the sky the circular hypothesis of course predicts essentially zero radial velocities, but the observed points range from zero to > ± 200 km s^{-1}.

We have examined the 74 planetaries in an area 20° x 20° centered on the galactic center and in an area 40° x 40° centered on the anti-center and for which both radial velocities and approximate astrophysical distances are available. Correcting for the solar motion of 10 km s^{-1} toward the galactic center, adopting R_o = 10 kpc, and dealing only with the absolute values of the measured radial velocities, we find (1) that the planetaries within 5 kpc of the galactic nucleus have radial motions in the range 0 - 200 km s^{-1} and a mean of 75 km s^{-1}; (2) that those 5 - 10 kpc from the nucleus have radial motions in the range 0 - 140 km s^{-1} and a mean of 38 km s^{-1}; and (3) that those 10 - 15 kpc from the nucleus have radial motions in the range 0 - 70 km s^{-1} and a mean of 32 km s^{-1}.

The trend of these results suggests several conclusions. First, the increase of the mean and extreme absolute values of radial velocity with decreasing galactocentric distance appears to reflect the greater orbital speed of objects as they approach perigal in their non-circular galactic orbits. Second, many of the objects in the central part of the galaxy that have small radial velocity may have large total orbital speeds but with most of the velocity in the transverse direction. Finally, the spatial concentration of planetaries toward the center would seem to be strong enough to suggest that many of them and their progenitor stars reside there permanently; they never experience enough gravitational acceleration to acquire high total speed or, therefore, large radial velocities as observed from here.

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DISCUSSION

Bonilha: How well does the $|z|$ distribution of planetary nebulae fit an exponential?
Wyatt: The fit is reasonable, but a strictly exponential distribution is physically disallowed because you have a distribution in $+z$ and in $-z$, and the implication therefore is that the density distribution has a cusp, a discontinuity at the plane. As a first approximation you could use an exponential. What I prefer to mean when I use the term scale height is that height at which if you squeeze all the planetary nebulae down toward the plane so that the distribution is homogeneous with density equal to that of the plane they extend to plus or minus a scale height.
Bonilha: I asked the question because the value $\langle|z|\rangle$ for the solar neighborhood is about 50% higher than the scale heights quoted by you.
Field: Does the scale height depend upon galacto-centric distance? One would suspect that it would, in view of the fact that the velocity dispersion does depend upon distance. If it does, wouldn't this modify the number of planetary nebulae you calculate for the galaxy?
Wyatt: I haven't looked into that at all. The $|z|$ distribution has to be derived locally and that is all we have attempted at the present time.
Cohen: Can you estimate by how much you may have overestimated the galactic population of planetaries due to the fact that Perek and Kohoutek's catalogue includes many objects that are not genuine planetaries?
Wyatt: We looked very hard at the local planetaries, a sample of just a few dozen. My feeling there would be that we are not using Perek and Kohoutek to anywhere near its entirety.
Ford: I would like to remark that if the Cudworth distance scale is correct, the luminosities of the brightest optically thin nebulae near the sun are equal to the luminosities of the brightest planetaries in M31.
Finzi: I would like to know if there is any correlation between the distance $|z|$ from the galactic plane and the mass of planetary nebulae.
Wyatt: The only thing one can say with certainty comes from the planetary nebulae in the globular cluster M15, which has an extraordinarily low mass of 0.01 $M_\odot$.
Longmore: I would like to point out that some work has been done in completing the search for low surface brightness planetaries in the southern hemisphere using plates from the UK Schmidt Southern Sky Survey. One of these has a galactic latitude of -85°, increasing the statistical sample on very high latitude systems from 3 to 4.