PLANETARY NEBULAE AND RELATED OBJECTS

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1. INTRODUCTION

This symposium is explicitly devoted to Planetary Nebulae which are associated to "dying" stars of moderate mass. All other bright nebulae in the Galaxy can be considered to be related to planetary nebulae in the sense that they are similar to planetary nebulae in many respects. However, in most cases, these "relatives"-nebulae correspond to astrophysical situations (as characterized by the evolutionary stage, chemical composition, physical parameters, etc.) which are completely different. A large variety of nebulae can be found in the sky. One goes from point-like objects like K3-50, which is a very compact HII region, or V1016 Cyg, possibly a proto-planetary nebula, through moderate size nebulae like the Crab Nebula (the famous supernova remnant, 5' size) or the Orion Nebula (the famous HII region around the Trapezium stars, 3' core), to large nebulae like the Trifid (HII region of 20' size) or NGC 6888 (which is associated to a WN6 star, about 30') and extremely large like the North America Nebula (NGC 7000, an emission-reflection nebula of about 2° size) and the Gum Nebula (probably a supernova remnant of approximately 36° diameter). We see that not only might they be different in size but also, and drastically, different in their physical nature. It is interesting to note, however, that as a rule nebulosities are found to accompany stars only in the early phases and in the very late phases of evolution. At this stage of the symposium we should have learned enough about nebulae related to old stars. Therefore, I have decided to talk about nebulae related to stars at the other end of evolution, that is classical HII regions. For convenience, I will use here the term "HII region" meaning implicitly an ionized nebula associated to, and ionized by, a young and massive star. By definition, these nebulae are interesting because they represent the first manifestation of new-born stars of high mass. In fact, in many cases one can detect an HII region (in the radio and/or in the infrared) well before being able to directly observe the exciting star.

I do not pretend to present a complete and exhaustive review on HII regions, but only to discuss some aspects of them with special emphasis

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on the problem of how to recognize them. Similarly, the references that I am going to give are selected by no cleverer a criterion than their being easily accessible to me.

2. OBSERVABLE PROPERTIES OF HII REGIONS

2.1 Optical Observations

When observed optically by direct photographs, HII regions, especially compact ones, may appear very similar to planetary nebulae in both size and shape. There is one aspect, however, that makes it easy to separate "bona fide" HII regions from planetary nebulae, and that is dust absorption. There are several methods for estimating the reddening from optical observations. For instance, by measuring the color excess of the ionizing star, by comparing the observed Balmer decrement with the theoretical one, by comparing the observed intensity of Hα (or an infrared line for very heavily obscured nebulae) with that expected on the basis of the radio flux. On the average HII regions are more reddened than planetary nebulae for two main reasons. One is that HII regions, being ionized by young and massive stars, are closely associated with big neutral and/or molecular clouds. Therefore, due to dust grains interspersed mostly with the cold gas, very often HII regions are heavily obscured to such an extent that they may even be undetectable in the optical range but still be strong sources at infrared and radio wavelengths. Note that heavy absorption on the scale of an HII region necessarily implies the presence of a massive cloud; for instance, a cloud of size 1 pc must have a total mass of at least 100 $M_\odot$ in order to cause an extinction of 5 magnitudes. Some examples are K3-50 (e.g. Wynn-Williams et al. 1977) or the compact sources in W3 (see e.g. Sullivan and Downes, 1973). The fact that in these cases one deals with local absorption is confirmed by the fact that it may vary by several magnitudes when moving a few arc minutes across a HII complex and/or by the presence of dark lanes on the bright nebula. An extreme example is given by the W58 region in which the component A(K3-50) suffers a visual absorption of about 27 magnitudes (Soifer et al 1976), while in front of the component C_1 (approximately 2' NE of K3-50) an extinction of about 100 magnitudes has been estimated (Wynn-Williams et al 1977). Also, an anomalously flat extinction law can be evidence for strong local absorption. In fact, once unreasonably large grains have been excluded, such a behaviour can only by due to either internal absorption (e.g. Mathis, 1970; Leibowitz, 1973) or to an extinction gradient across the source (e.g. Persson and Frogel, 1974; Panagia and Vettolani, 1977). Besides strong local obscuration, high reddening in front of an ionized region may also provide a statistical means for distinguishing HII regions from planetary nebulae. In fact, HII regions are located mostly in the spiral arms (as a matter of fact HII regions define the spiral arms; Georgelin and Georgelin, 1976) where the absorption is the highest in the Galaxy, whereas planetary nebulae, which are more evenly distributed in the disk, are only affected by an average, hence smaller, interstellar absorption. In addition, HII regions, being energized by main sequence OB stars, are, on the average, a factor of 10 (or more) intrinsically brighter than planetary nebulae and, therefore, can be observed to a farther distance, thus with a higher reddening. An example of this statistical effect can be found in the sample of small nebulae studied by Chopinet and Lortet-Zuckermann (1976). The nebulae which are probably HII regions are significantly more reddened ($<c(H_\beta)> = 1.3$ with a dispersion of ±0.5) than those which are probably planetary nebulae, for which $<c(H_\beta)> = 0.5$ with a dispersion of ±0.5.

The optical spectrum provides a means for ascertaining the nature of a nebula. The spectra of HII regions are characterized by a relatively lower excitation than planetary nebulae. This is because main sequence OB stars are not expected to have an effective temperature higher than about 50,000 K (Conti, 1975). A representative temperature for O type stars may be about 40,000 K, although there are indications that it may be significantly lower (cf. Stothers, 1976; Macchetto and Panagia, 1977). Therefore, in HII regions the heavy elements are less ionized than in planetary nebulae and the gas temperature is lower. On this basis some criteria for distinguishing HII regions from planetary nebulae have been established. For instance, Chopinet and Lortet-Zuckermann (1976) have found that a ratio $I(4959 + 5007; [OIII])/I(H_\beta) > 7$ (essentially a "temperature" criterion) identifies a region as a planetary nebula. Also, the detection of the HeII λ4686 line (i.e. $I(4686)/I(H_\beta) > 0.10$) has been suggested as a criterion for identifying a planetary nebula. This would be an "ionization" criterion in that only high temperature stars ($T > 70{,}000$ K) are expected to be able to ionize helium twice in appreciable amounts. However, one has to be careful in applying these criteria, because they are valid only in a statistical sense, and in some cases they could provide a wrong answer. For instance, Danziger (1974) has measured a ratio $I(4686)/I(H_\beta) = 0.36$ in the HII region G353.1 + 0.7 (a component of NGC 6357). There is no doubt that it is a genuine HII region because it is associated with massive stars, its luminosity is high and a strong far infrared source is associated with it. The possible explanation is that one of the exciting stars has a spectral type WC6 (Georgelin, 1975), which may give rise to a relatively strong HeII λ4686 line via three possible mechanisms: 1) collisional ionization by interaction of stellar wind from the WR star with the surrounding medium; 2) scattering by dust of a "photospheric" emission line λ4686; 3) possible "anomalous" excess of hard ultraviolet radiation ($h\nu > 54.4$ eV) in the spectrum of the WR star. Whatever the exact mechanism could be, the fact is that "normal" HII regions in some cases may escape simple classification criteria.

2.2 Infrared Observations

HII regions are observed in the infrared to have a strong excess of radiation relative to the gas emission; the current interpretation is that this is due to emission by dust grains (see e.g. Panagia, 1977). The aspects which characterize the infrared emission from HII regions are: 1) The infrared spectrum peaks around 50 to 100 μm and is about a factor of two broader than that of an isothermal nebula (see the discussion by Natta and Panagia, 1976). This is typical of HII regions because it implies the presence of a massive cloud. For instance, a source must have a total mass of at least 40 $M_\odot$ in order to have total IR luminosity of 3×10^5 $L_\odot$ and a peak wavelength of 60 μm. 2)A broad band around 10 μm; usually it is observed in absorption implying large optical depths in the IR and in the visual (e.g. Gillett et al. 1975). This band is commonly attributed to some silicate material and has never been observed in the spectrum of a planetary nebula. 3) The flux shortward of about 3 μm is often lower than the extrapolation of the gas spectrum from the radio range; this again implies large optical depths. 4) The total infrared luminosity is that typical of main sequence O type stars or higher (say from $\sim 10^4$ $L_\odot$ to $\sim 10^7$ $L_\odot$, as for some components of W51). The ratio of the total infrared luminosity to the Lyman-α luminosity is around 14. Such a high value is only possible if surrounding the ionized region there is a massive dusty cloud; otherwise, the ratio L(IR)/L(Ly-α) can hardly be higher than 5 (cf. Panagia, 1974; Natta and Panagia, 1976).

We see that these aspects all require the presence of a large dusty cloud physically associated with the ionized region. It is clear that this is possible for an HII region, which is ionized by a massive star and is located in a zone of active star formation, thus rich in interstellar material at high density. Conversely, all this is impossible for planetary nebulae, which are isolated objects and whose total nebular mass is on the average ~ 0.2 $M_\odot$ (but with a large dispersion: see e.g. Perinotto, 1975) and cannot be higher than about 2.6 $M_\odot$ (upper limit estimated as the total mass lost by the most massive star ($M \approx 4$ $M_\odot$), which eventually does not undergo a supernova explosion; Fusi-Pecci and Renzini, 1976). In addition, grains in planetary nebulae are mostly made of graphite-like materials (Panagia et al. 1977 a,b) so that for any given radiation field, their equilibrium temperature is much higher than that of interstellar grains. Therefore, irrespective of the luminosity, it is very unlikely for planetary nebulae to have a spectrum peaking at far infrared wavelengths. For all these reasons, infrared observations are not only important for studying the conditions in the objects themselves but also to ascertain their nature.

2.3 Radio Observations

Besides the obvious but not trivial advantage of permitting one to "see" throughout the entire Galaxy, radio observations of HII regions give us some more ways to identify them as such. A comparison of the radio flux, which is due to free-free emission, with the intensity of some hydrogen line (usually Hα if it is detectable; recently Bα and Bγ have been employed for this purpose, Soifer et al. 1976) can give an accurate estimate of the absorption in front of the region. Hydrogen recombination radio lines can be used to determine the radial velocity of the nebula and to estimate a kinematic distance to it. This is an important aspect, because for heavily obscured regions it is the only way of measuring the radial velocity and therefore of estimating a distance.

The association of HII regions with molecular clouds can readily be ascertained by means of radio observations. Often the molecular line emission (most commonly the $J = 1 \rightarrow 0$ transitions of ^{12}CO and ^{13}CO at 115.2712 and 110.2014 GHz, but also many others) is observed to be peaked at the position of an HII region. This is already circumstantial evidence

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that the corresponding molecular cloud is physically associated with the HII region. A confirmation can be given by the comparison of the radial velocity of the H-recombination lines to that of the molecular lines. A close agreement indicates that the ionized region and molecular cloud are truly associated with each other. An estimate of the mass of the molecular cloud and a study of the profile of the lines can provide the final proof that we are really dealing with an HII region. In fact, molecular clouds associated with HII regions are massive clouds (typically 10^4 $M_\odot$) and display emission line profiles which are only a few km/s wide; on the contrary the molecular emission coming from sources associated with planetary nebulae or similar objects requires little emitting mass and displays a broad profile (cf. Mufson et al. 1975; Zuckermann et al. 1976). In addition to emission of molecular lines, absorption lines due to neutral hydrogen and to molecules (e.g. H_2CO) are also observed. Since hydrogen is present all over the Galaxy, measuring a 21 cm absorption line on the spectrum of an HII region usually can only give us an indication of the distance of the region. Molecular absorption lines, instead, in principle can provide us information on both the distance and/or the kinematics of a region and its possible association with the molecular clouds (e.g. Bieging, 1975).

3. CONCLUSION

Now, we have seen some possible way of recognizing an HII region and distinquishing it from other nebular objects. All the reviewed methods are based on three intrinsic properties of HII regions and associated clouds, which are:
1) Young age of the exciting star;
2) Availability of large amounts of mass;
3) High luminosity of the exciting star, and the fact that it is a main sequence star.

Points 1) and 3) are self-explanatory. Point 2) derives from the fact that a massive star necessarily has been formed from a massive cloud and, being young and short-lived, is most likely found still associated with the parent-cloud. The most powerful criteria for recognizing a compact HII region are based on this point. In fact, heavy local obscuration, far infrared emission and spatial and kinematic coincidence with molecular clouds are all evidence for a large nebular mass. Applications of point 3) are the criteria based on the excitation as determined from the line spectrum. Also, direct observations of the star can add information on this; moreover, high reddening of non-local origin may indicate a large distance and, since the region can nevertheless be observed, a high luminosity.

A chemical composition corresponding to unevolved but extreme population I objects will show the young age of the region (point 1)). To do this one studies the emission lines in the optical range (permitted of H and He, forbidden of heavy elements), in the infrared (fine structure lines of heavy elements) and in the radio domain (recombination lines of H and He). Also, the presence of a strong silicate band around 10 μm can be taken as an indication of a "normal" chemical composition, at least in the sense that any enrichment of heavy elements due to local evolution must have been negligible.

The determination of absolute quantities such as the luminosity and the mass and the size of the nebula requires some knowledge of the distance. Usually for HII regions the distance is estimated either from observations of the exciting star(s) (once m_V, (B-V) and the spectral type are measured, the distance follows directly: spectroscopic distance) or from measurements of the radial velocity of the emission lines (by adopting a model for the rotation of the Galaxy: kinematic distance). However, both kinematic and spectroscopic distances may reliably be determined only for HII regions. Otherwise, it is well known that kinematic distances may be in great error for planetary nebulae (see e.g. Churchwell et al. 1976) and spectroscopic distances are reliable only for main sequence stars. Therefore, one needs some clear indication that a given region is an HII region before being justified in relying on an estimate (either kinematic or spectroscopic) of the distance. In addition, considering that there is already a 50% probability that kinematic and spectroscopic "distances" agree reasonably with each other (within an uncertainty of 50%) just by chance, an argument based on their similarity cannot have any high significance. Therefore, an estimate of the ionized mass cannot provide any good evidence about the nature of the source, because an uncertainty of a factor of 2 in the distance makes an uncertainty of a factor $2^{2.5} = 5.7$ for the mass. Furthermore, just for compact regions, which are those most similar morphologically to planetary nebulae, the ionized mass may be rather low because of the high gas density. Also, the absolute luminosity is not always easy to determine accurately. In this case, however, there is the advantage that estimating it can give us immediate information about the exciting star, without any further problem introduced by the gas density. Since HII regions are expected to have luminosities and Lyman continuum photon fluxes higher than about $10^4\ L_\odot$ and 10^{47} photon/s, respectively (Panagia, 1973), while for planetary nebulae these values are almost the upper limits, the absolute luminosity may be used as a criterium to separate the two classes of objects. However, the fact that in order to estimate the luminosity one needs to estimate a distance and that this latter in turn requires some knowledge about the nature of the objects under study, may make all this a circular argument with no way out. Let us take for example the case of K3-50: it is well established that it is an HII region (Harris, 1975; Israel, 1976; Wynn-Williams et al. 1977). However, interpreting it as a planetary nebula, one would derive a distance of $\sim$1.5 Kpc, deduced by assuming a nebular mass of 0.2 $M_\odot$. Then, the Lyman continuum photon flux would be $\sim 10^{48}$ photons/s, which would be consistent with the "assumption" that K3-50 be a bright planetary nebula.

I conclude that, paradoxically, the classification criteria based on "absolute" quantities may be of marginal use, whereas those based on apparently more indirect evidences should seldom fail to work.

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DISCUSSION

Perinotto: I would like to say something about the distinction between planetaries and related objects, discussing the peculiar object M 1-67. This nebula has been classified either as a planetary nebula, a compact HII region, or a ring nebula expanding from a population I Wolf-Rayet N-type star. From an aperture synthesis map obtained by Dr. Felli at Westerbork, carefully overlayed with an Hα + [NII] photograph by Minkowski, a very good optical-radio correlation results to the limit of the radio resolution (∿7"). It is becoming clear now that this property, good optical-radio correlation to the resolution of the radio maps so far obtained, is a rule for planetaries, with the only distinct exception up to now of NGC 7027. A good correlation is actually also valid for ring nebulae. We know on the other hand that in the case of compact HII regions the opposite situation is apparently true. A good example is the compact HII region, S 88 B, where the anticorrelation is strong to a large scale. Therefore the comparison between optical and radio isophotes may be a practical criterion of distinction between compact HII regions and other objects. Of course, in this frame, according to this criterion NGC 7027 would be a compact HII region.

Peimbert, M.: At the moment, M 1-67, in my opinion, cannot be safely considered either as a planetary nebula or as a compact HII region. Further work is necessary, in particular, direct measurements of the electron density and of the expansion velocity to test the ring nebula hypothesis.