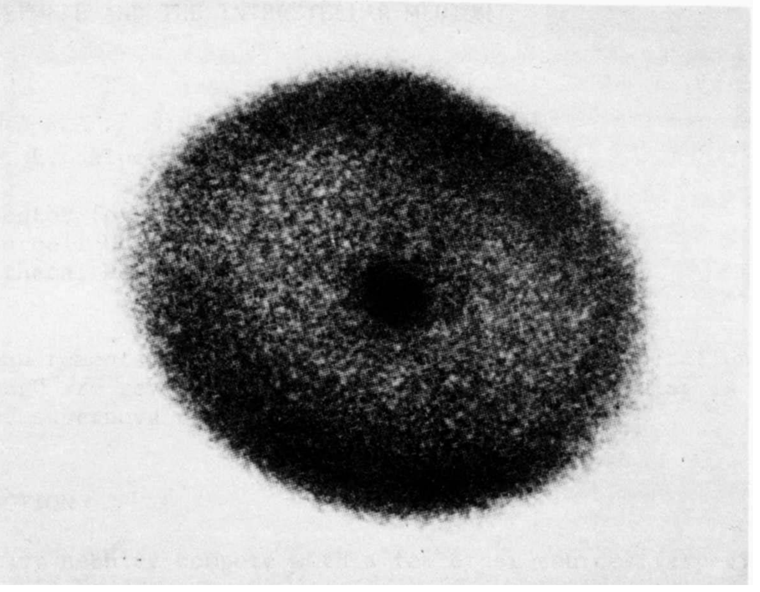

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SESSION VIII

PLANETARY NEBULAE AND THEIR INFLUENCE ON THE GALAXY

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PLANETARY NEBULAE AND THE INTERSTELLAR MEDIUM

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The requirements of the interstellar medium for ionization, heating and "stirring" are reviewed. The role of planetary nebulae is compared with that of supernova remnants and of OB-stars.

1. INTRODUCTION

Planetary nebulae compete with a few other sources (especially early-type stars and supernova remnants) in supplying mass and energy to the interstellar medium. The input rates are rather uncertain (§ 2, Table 1) and one might have hoped that properties of the interstellar medium (ISM) could be used to draw some inferences about planetary nebulae. Unfortunately our views of the ISM have become more complex recently (§ 3), frustrating inferences at the moment.

To start with some of the most basic properties of the ISM (Spitzer 1968): The mean density of hydrogen near the galactic plane is $\bar{n} \sim$ 1 H cm^{-3} in total and about half of this value if the very dense molecular clouds are excluded. Even after this exclusion the "normal HI-regions" are usually subdivided into: (1) "standard clouds" with "low temperatures" ($T \lesssim 100°K$) indicated by narrow spectral features, a fairly small filling factor ($f \sim 0.01$ to 0.03) with "one cloud per $\sim$ 130 pc along a typical line of sight" and contributing $\bar{n}_{cl} \sim 0.3\ cm^{-3}$; (2) the "intercloud medium" with "higher temperatures" and "larger filling factors," indicated by broad spectral features in 21cm-emission and by weak 21cm-absorption, contributing $\bar{n}_{ic} \sim 0.2\ cm^{-3}$ (Baker and Burton 1975, Burton 1976). The velocity dispersion (3-dimensional, root-mean-square) is $\sim$ 15 km s^{-1} and the mean (not root-mean-square) electron-density near the galactic plane, $\overline{n_e} \sim 0.03\ cm^{-3}$ is fairly reliably known from pulsar dispersion measures (Gómez-González and Guelin 1974).

For comparison with § 2 we note various energy input rates required by the ISM. We shall express these rates "per H-atom sec^{-1}" by dividing the rates per unit volume by the H-atom density, taken as $\bar{n} = 0.5$ H cm^{-3}:

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The ionization rate ζ required to maintain $\bar{n}_e = 0.03\ cm^{-3}$ depends on the recombination rate and hence on the square of the electron density,

$$\zeta \sim \left[\langle n_e^2 \rangle (0.03)^{-2}\right] \times 1 \times 10^{-15}\ \text{ph. } H^{-1}\ s^{-1}, \qquad (1)$$

where ph. stands for ionizing photons ($h\nu > 13.6$ eV). The statistics and velocities of "standard clouds" indicate collisions every $10^{7\pm1}$ years (Spitzer 1968) and the "stirring-rate" r_{st}, i.e. the rate at which bulk kinetic energy is supplied to replenish the motion of whole clouds, is

$$r_{st} \sim 5 \times 10^{-15\pm1}\ \text{eV } H^{-1}\ s^{-1}. \qquad (2)$$

The heating rate r_h required to keep the intercloud medium (average density $\bar{n}_{ic}$) "hot" depends on the actual temperature T and on typical internal densities n_{int} (since radiative cooling is initiated by collisional excitation). For T $\sim$ 500°K we have

$$r_h \sim (\bar{n}_{ic}/0.2)(n_{int}/1) \times 5 \times 10^{-15}\ \text{eV } H^{-1}\ s^{-1}. \qquad (3)$$

With typical energies of $h\nu \sim 30$ eV per ionizing photon, the energy equivalent of the ionization rate in equation (1) is of order 10^{-13} eV H^{-1} s^{-1}, appreciably larger than the values in equations (2) and (3).

2. VARIOUS ENERGY SOURCES

In Table 1 are listed various input-rates contributed by planetary

TABLE 1

Various input rates for the ISM

Source	Mass injection ($M_\odot\ yr^{-1}$)	Kinetic energy "stirring rate" r_{st} (10^{-15}eV $H^{-1}s^{-1}$)	Ionizing photon rate: Local ζ (10^{-15}ph.$H^{-1}s^{-1}$)	Ionizing photon rate: Galaxy total (10^{52}ph.s^{-1})
Supernova Remnants	0.04	10	2	0.5
"Free" OB-Stars	?	0.3	(10)2	(2)0.5
Planetary Nebulae	0.2 to 2	<0.1	1 to 10	0.2 to 8

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nebulae and by the two main rival sources, supernova remnants and early-type stars. Since this is a symposium on planetary nebulae I give a range of values for this source; for the other two sources I only give "typical values" and references to some of the original papers where numerical controversies are discussed: for supernova remnants see Maza and v. d. Bergh (1976), Salpeter (1976), Tammann (1977), for OB-stars see Cruz-González et al. (1974), Terzian (1974), Elmegreen (1976) and Lyon (1976). I omit low-mass flare-stars and accreting white dwarfs as further rival sources: they may yet turn out to be important but too little is known about them at present.

I will not discuss the mass injection rate (in spite of its importance) since the talks by Wyatt, Weidemann and Tinsley deal with this topic. I merely note that most estimates for number densities of near-by planetaries are fairly close to the values of Cahn and Wyatt (1976), e.g., a column density of about 20 kpc^{-2}. An appreciable fraction of the elements beyond He, injected by planetary nebulae, may appear in the form of dust grains. The rate may be sufficient to replenish the interstellar grains about once in the lifetime of the Galaxy. This grain injection is therefore potentially important, but likely to be masked by grain destruction in supernova remnants and formation in dense molecular clouds (Salpeter 1977).

The "stirring rate" for injecting bulk-energy into cloud-motion comes overwhelmingly from supernova remnants (which can also compress and "reform" clouds). The equivalent rate from planetary nebulae is uncertain but even the largest estimate is uninterestingly small: Although there is observational and theoretical evidence that nebular shells accelerate during their expansion (Bohuski and Smith 1974, Ferch and Salpeter 1975), Bonilha (1977, unpublished) has shown that expansion velocities above 100 km s^{-1} are unlikely and the resulting blast-waves in the ISM are of little consequence.

The third column in Table 1 gives ionization rates (per H-atom) in the solar vicinity, but averaged over the whole column perpendicular to the galactic plane. For the early-type stars I have omitted altogether radiation from stars which are still embedded in dense clouds since the radiation would not escape into the general ISM. For the remaining "free" stars the number in brackets refers to O-stars, the second number to B-stars (we shall see in § 3 why the O-stars are less efficient in contributing to $\bar{n}_e$). The contribution from planetary nebulae refers to radiation from central stars of optically thin nebulae: Although the distance scale (and hence the number of observable nebulae) is now reasonably well-known, the mean bolometric luminosity L_c of a central star, and hence the number-rate of emitted photons (Terzian 1974), is rather uncertain. For Table 1 I have chosen the range of $L_c \sim (2000$ to $10^4) L_\odot$ (with the lower end more likely) and have also allowed for the possibility of a comparable number of still luminous central stars with nebulae so old and faint to escape detection. Theoretically, the possibility of such UV-stars (Hills 1972, Lyon 1975) remaining luminous longer than the nebulae depends on the mass of unburned hydrogen in the stellar envelope when the nebular ejection ceases. This mass is quite uncertain theoretically and a satellite survey in the UV for hot sources (unassociated with visible stars) would be most welcome.

In discussing the ionization equilibrium for an intergalactic medium (and, possibly, also for the gas in the outermost regions of a warped galactic disk), the Galaxy's total emission rate of ionizing photons is of importance. Estimates for this quantity are given in the last column of Table 1. The uncertainty in the contribution from central stars of planetary nebulae contains an additional factor of 3 or 4, the ratio of total mass to disk mass of the Galaxy: It is not clear whether the ratio of ionizing luminosity to total stellar mass is smaller in the nuclear bulge (intermediate stellar population II) than in the galactic disk. Present indications are that these ratios are comparable, since (i) the number of planetary nebulae per total mass is not much lower in elliptical galaxies (Ford, Jacoby and Jenner 1977) than in spirals and (ii) the central star should depend less on the original stellar mass than does the ejected nebula.

3. RECENT VIEWS ON THE INTERCLOUD MEDIUM

Before UV results from the Copernicus satellite became available, it seemed possible to explain data on the neutral hydrogen in the galactic disk by means of the simple and elegant "two-phase model" of the ISM, reviewed by Dalgarno and McCray (1972). This model assumed pressure equilibrium and a uniform distribution of penetrating ionizing radiation in the form of cosmic rays or X-rays. If one assumes $\zeta \sim 10^{-15}$ ph.$H^{-1}s^{-1}$ in this penetrating radiation, one can obtain two phases: Phase 1 with $n_{int} \sim 20$ cm^{-3}, T $\sim$ 60°K (and a small filling factor to contribute $\bar{n}_{cl} \sim 0.3$ cm^{-3}) represents the "standard clouds"; Phase 2 with $n_{int} \sim 0.2$ cm^{-3}, T $\sim$ 6000°K, $n_e \sim 0.03$ cm^{-3} and a large filling factor ($f \gtrsim 0.9$) would represent a "ubiquitous" intercloud medium. In this model the same radiation takes care of ionization and heating (equations [1] and [3]), but "stirring" is not considered.

Over the last few years, Copernicus results (Spitzer and Jenkins 1975) and cosmic-ray and X-ray data have complicated the matter: Supernova remnants indeed produce X-rays, but only with $\zeta \sim 10^{-16}$ instead of $\sim 10^{-15}$ (and cosmic rays are probably less important), and are associated with highly ionized regions (York 1977) characterized by the presence of OVI. Furthermore, the neutral intercloud medium is not as "ubiquitous" and uniformly hot as previously hoped: Only a fraction of the $\bar{n}_{ic} \sim 0.2$ cm^{-3} corresponds to T > 1000°K, more of it is contributed by features which are intermediate between Phase 1 and Phase 2. For these "substandard clouds," or "Phase 1.5," the 21cm-absorption is weak but measurable with the sensitive Arecibo beam (Dickey, Salpeter and Terzian 1977) and measured temperatures range from $\sim$ 100 to over 1000°K.

The "present fashion" is unfortunately much more complex with more than two phases and considerable variation of pressure as well (for reviews see Salpeter 1976, McKee and Ostriker 1977): Phase 1 is roughly as before but the internal temperature ranges from $\sim 20°K$ to $\sim 100°K$; some Phase 2 may still survive but with a smaller filling factor and contributing $< 0.1\ cm^{-3}$ to the neutral $\bar{n}$. In addition we now have what I called "Phase 1.5" which contributes much of the neutral $\bar{n}_{ic} \sim 0.2\ cm^{-3}$ but contributes very little to the electron density n_e. This "phase" is not uniform but consists of "sub-standard clouds" which range all the way from Phase 1 to Phase 2 (temperatures from $\sim 100°K$ to a few thousand °K) and require some heat source, according to equation (2). An appreciable fraction of space is filled by Phase 3, the highly ionized medium which is recognized (York 1977) by the presence of OVI and is at very high temperature and very low density ($T \sim 10^6 °K$, $n_e \sim 10^{-3}\ cm^{-3}$).

None of these "new" phases contain enough electrons to furnish the observed $\bar{n}_e \sim 0.03\ cm^{-3}$ and one has to postulate an additional Phase 4: The sources contributing to the third column in Table 1 mainly emit photons with $h\nu \lesssim 30$ eV which produce fully ionized HII-regions, or "Strömgren spheres," in the ISM. The temperature of this phase is $\sim 10^4 °K$ and the internal electron density is controlled by whatever the neutral density was before the ionization. B-stars and planetary nebulae are a relatively frequent occurrence so that they can ionize an appreciable fraction of the volume of the low-density ($n_{int} < 0.2\ cm^{-3}$) intercloud gas (i.e., the regions outside "standard" and "sub-standard" clouds). The factor in square brackets in equation (1) need not be much larger than unity, i.e., the photons are utilized efficiently as regards $\bar{n}_e$. By contract, the O-stars (Elmegreen 1976) are rare but have such a high luminosity that they ionize all the clouds in a direct line to the star and they live long enough that the ionized and heated clouds can disperse. O-stars thus produce Strömgren spheres with $n_{e,int} \gtrsim 1\ cm^{-3}$, the square bracket in equation (1) is large and these stars are "inefficient." Observations on fluctuations over the sky of the emission measure might eventually give direct evidence on the distribution of n_e and might, for instance, be able to rule out the upper value for planetary nebulae in column 3 of Table 1.

The most controversial aspect of the neutral ISM at the moment is the question of heating the "Phase 1.5": The temperature of a "sub-standard cloud" measured by 21cm-studies is only a harmonic mean temperature and might represent a cooler cloud-core surrounded by a hotter envelope which is being evaporated off (McKee and Ostriker 1977). Two rival energy-sources may be heating by (i) cloud-cloud collisions and (ii) photoelectric effect on grains. Because of the relatively frequent occurrence but short lifetime of central stars of planetary nebulae, surfaces of clouds are alternately subjected to ionization, and recombination. This alternation, plus turbulence, may be conducive to producing a hot envelope but no calculations are available as yet.

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DISCUSSION

Dopita: With regard to the possibility of grain destruction by supernovae, the nitrogen line strength is a function of SNR diameter and can be fitted by a model of "ice" grains melted by the radiation pulse of the supernovae out to a distance of about 25 parsecs.

Salpeter: My own remarks referred to the sputtering of refractory grain cores, which requires more energetic particles than the sputtering of ices. The "radius of destruction" for refractory material is therefore smaller than your 25 parsecs.

Field: Concerning the sputtering of more refractory things, do you find any significant difference between silicates and graphite?

Salpeter: Graphite may be slightly easier to sputter than silicates, but the difference is small.

Panagia: I got the impression that in the "4 phase" model of the interstellar medium there are as many free parameters as unknowns. Is this correct? If it is, what is the significance of such a world?

Salpeter: In fact there are probably more free parameters than observed quantities at the moment! Nevertheless one cannot choose a simpler model,

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because each phase and each complexity (such as deviations from equilibrium) is suggested by observations. That is why I said one cannot derive parameters on planetary nebulae from the interstellar medium.

Field: In the computation of the kinetic energy, did you include the expansion of the shell, and the velocities of the planetaries with respect to the plane?

Salpeter: Yes, I included both expansion velocity and stellar velocity in estimating the kinetic energy. Furthermore, only a fraction results in bulk kinetic energy of the interstellar medium and the true value should be even smaller than my estimate.

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