PHYSICAL CHARACTERISTICS OF IONIZED GASEOUS NEBULAE*

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INTRODUCTION

The chief advantages of the Space Telescope over conventional ground-based telescopes, namely, ability to observe ultraviolet radiation and high angular resolution, make it particularly valuable for research on gaseous nebulae. These objects are interesting not only in themselves, but also because they provide an opportunity to measure the abundances of the common light elements in the first two rows of the periodic table. H II regions are samples of interstellar matter from which stars are now forming in our galaxy, and in other galaxies. Planetary nebulae are objects approaching the end of their evolution as luminous stars, in which an outer shell has been thrown off and is returning to interstellar space. They represent one of the most prolific sources of mass return to interstellar matter at the present time in our galaxy. Thus both these classes of nebulae provide important and different information on abundances. Supernova remnants, although considerably rarer, in general contain a mixture of highly processed material being returned to interstellar space and interstellar gas being swept up by it. Physical conditions in them are considerably more complicated than in photoionized planetary nebulae and H II regions, and it is therefore not so straightforward to go from the observed strengths of the lines to the deduced abundances of the ions that emit them. However, the potentiality of understanding some of the extreme products of nucleogenesis lies in these remnants.

The great advantage of gaseous nebulae for abundance determinations is that the strengths of emission lines are directly related to the abundances of the ions that emit them. Thus complications due to radiative transfer effects, such as the continuous opacity, and the resulting relationship between the strength of an absorption line and the abundance of the ion responsible for it, are much smaller in gaseous nebulae than in stellar atmospheres. The difficulty in the past has been that only a limited number of the stages of ionization of common elements in gaseous nebulae has been observable. Many common ions such

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as C^{+}, C^{++}, C^{+++}, N^{++}, N^{+++}, O^{+++}, O^{++++}, etc., do not have strong emission lines in the optical spectral region. Therefore, the abundances of such ions have been deduced from ionization-equilibrium calculations, or from simplified interpolation schemes based on such calibrations. The models are invariably simplified for practical computational reasons; in addition some of the rates of physical processes important in the ionization equilibrium are only poorly known. As a result, comparisons of these models with observable quantities always show discrepancies. Therefore the calculations or estimates of the abundances of the unseen stages of ionization contain a considerable amount of uncertainty. However, nearly all ions have lines somewhere in the observable region, from the satellite ultraviolet through the optical to the infrared. Numerous ions are observable only in the ultraviolet, and the Space Telescope thus is a very important tool in these abundances studies.

All gaseous nebulae that have been observed carefully have turned out to contain very many density fluctuations or density inhomogeneities. The better the angular resolution of the observing system used, the smaller the angular size of the inhomogeneities that have been observed. Clearly the physical conditions in a small volume of space, such as a "clump", "knot", "front", or low-density minimum between these structures are more informative than the average physical conditions over the nebula. The power of the Space Telescope to measure very small areas in the sky will be of great benefit in nebular studies.

Supernova remnants are different from planetary nebulae and H II regions in that the primary excitation mechanism in most supernova remnants is "collisional" or "shock-wave heating", that is, the conversion of kinetic energy into thermal energy, rather than photoionization the conversion of photon energy into thermal energy. As a result, supernova remnants have different spectra from photoionized nebulae, with a wide range of temperature and ionization occurring in a relatively small volume in space. Again, the wide range of ultraviolet spectrum, detectable only from above the earth's atmosphere, will greatly increase our ability to analyze these objects. The high angular resolution also will make it possible to study in much more detail the physical processes going on in supernova remnants, and thus in the end to determine the abundances of the elements in them more accurately.

In the following sections I will discuss planetary nebulae in some detail, and then those aspects of H II regions and supernova remnants that differ from planetary nebulae, outlining the main opportunities for nebular research with the Space Telescope. A vast amount of work has been done on these objects and I will not attempt to summarize it here, but simply refer to books such as Osterbrock (1974) and Spitzer (1978) and review articles such as Miller (1974), Salpeter (1977) and Chevalier (1977).

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PLANETARY NEBULAE

Planetary nebulae are well understood as photoionized nebulae with very hot central stars. They range in angular size from below the limit of resolution of ground-based telescopes to several minutes of arc. Many planetary nebulae have fairly high symmetry, usually of a kind that can be interpreted as symmetry about an axis. They have emission-line spectra ranging up to high ionization, such as [Ne V] and [Fe VII] in some cases and [O III] and [Ne III] in nearly all cases. The electron densities and temperatures are of order $N_e \approx 10^{3\pm2}\,\mathrm{cm}^{-3}$ and $T \approx 10^{4\pm0.3}\,\mathrm{K}$. Collisionally excited lines (in the optical region nearly all of them forbidden lines) from abundant ions with excited levels within a few volts of the ground level dominate the spectrum, along with recombination lines of H I, He I and He II. The energy input to the gas occurs through photoionization, which thus fixes both the ionization equilibrium and the thermal equilibrium at each point in the nebula. The planetary shells are expanding with velocities that increase more or less linearly from zero at the center, to approximately 25 km/s in the main part of the [O III] emitting regions. Infrared measurements show that many planetary nebulae contain heated dust. Furthermore, observations of [O I], [N I] and even CO (Mufson et al. 1975) and H_2 (Treffers et al. 1976) molecules show they also contain, or have very close to them, heated clumps of neutral gas.

From an evolutionary standpoint, planetary nebulae represent a relatively short-lived stage of a highly evolved star, which has exhausted its central H and He nuclear fuels and is losing its outer envelope as the remnant stellar core contracts toward the terminal white-dwarf stage. The luminosity of the star, which photoionizes the gas in the shell it threw off, is probably derived from H burning in a shell source just outside the C and He zones containing most of the mass of the star, gravitational contraction of the outer parts of this core, and cooling of the degenerate inner part of the core. The whole lifetime of a particular object as an observed planetary nebula is of the order of a few times 10^4 yr.

The basic simplicity of nebular astrophysics results from the fact that the density is very low. Nevertheless, Coulomb collisions quickly thermalize electrons produced by photoionization. Two-body collisions of these electrons with positive ions produce ions or atoms in excited states which in most cases emit a line photon before suffering a collision. The specific intensity, or surface brightness, in a given emission line can thus be written in a form

$$I(\lambda) = \int N_e\, N_i\, \varepsilon(\lambda,T) \cdot b(\lambda) \cdot h\nu\, dV. \qquad (1)$$

Here N_i is the density of the ion responsible for emission of the line, ε is the rate coefficient for the two-body process responsible for populating the upper level of the line, and b is a factor giving the fraction of these population processes that are followed by emission of a photon in the line in question. At low densities, b depends almost

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entirely on transition probabilities; if the density is high enough so that collisional deexcitation becomes important it also depends on the collisional rates. The integral is over the volume of the projected area of the entrance aperture extended along the line of sight through the nebula. In the very simplified situation in which the nebula has uniform density and temperature, the ratio of strengths of two lines gives directly the ratio of abundances of the responsible ions:

$$\frac{I(\lambda_1)}{I(\lambda_2)} = \frac{N(i_1)}{N(i_2)} \; \frac{\varepsilon(\lambda_1,T)}{\varepsilon(\lambda_2,T)} \; \frac{b(\lambda_1)}{b(\lambda_2)} \; . \qquad (2)$$

In general, for recombination lines the temperature dependence of ε is weak, approximately $\propto T^{-1}$, and does not differ greatly from one line to another. Hence equation (2) serves well for calculating the ratio of two recombination lines, such as Hα/Hβ, or for determining the relative abundances of H^+, He^+ and He^{++} from their recombination lines, even if the temperature varies and its average value is roughly known. On the other hand, for collisionally excited lines,

$$\varepsilon = \frac{8.629 \times 10^{-6}}{T^{1/2}} \; \frac{\Omega(i,j;T)}{\omega_j} \; \exp(-\chi_{ij}/T), \qquad (3)$$

where Ω is the mean value of the collisional strength (a dimensionless form representing the main dependence of the collision rate) between the two levels, ω_j is the statistical weight of the upper level, and χ_{ij} is the excitation energy of the upper level with respect to the lower level. It can be seen that a small error in the temperature causes a large error in the local excitation rate, and hence in the derived relative abundances.

A very large amount of data on relative line intensities in planetary nebulae has been obtained in the ground-based optical region, and much of it has been collected and made available by Kaler (1976). The amount of extinction along the path and within a given nebula can be calculated by comparing observed and calculated H I recombination line ratios, using a standard interstellar extinction curve derived from measurements of stars. Ratios involving optical, infrared and radio-frequency (free-free) measurements generally give concordant ratios except in cases where the extinction varies radically across the face of the nebula, such as in NGC 7027 (Scott 1973, Seaton 1979). The extinction derived in this way can then be applied to all the observed relative line strengths, to determine the intrinsic relative intensities emitted by the gas in the nebula.

In principle, the best way to derive abundances from the observational data is by using calculated models of the planetary nebula to which they refer. The assumed geometry, density distribution, properties of the central star and abundances should all be varied, and agreement of all observed line strengths (as well as spectrum and

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magnitude of the central star, if they are observed) with one of these models determines all these quantities. A recent example is the series of models of NGC 7027 calculated by Shields (1978). In every case known to me, the agreement between observed data and model predictions is less than perfect, no doubt because the actual physical structure of the nebula is more complicated than any models yet computed, and because the rates of some of the physical processes are not yet known to sufficient accuracy. Usually the best overall agreement of observed data with quantities believed to be most accurately calculated is taken as the test of a model.

Since models are difficult, time consuming, and expensive to compute, empirical methods, based on interpolations among models or among observed nebulae, are often used to derive abundances. First of all, mean values of the temperature can be calculated using equation (2) for any ion in which two levels with different excitation potentials give rise to lines in the observable spectral region. The best example is [O III], for which the main dependence of the intensity ratio [I(λ5007) + I(λ4959)]/I(λ4363) is exponential on the temperature, with also a weak density dependence for $N_e \gtrsim 10^5$ cm^{-3}. Other ions with energy-level structure permitting temperature determinations of this type are [N II] (λ6583 + λ6548)/λ5755, [S III] (λ9532 + λ9069)/λ6312 and [Ne III] (λ3697 + λ3869)/λ3342, although the last line is so far into the ultraviolet that accurate ground-based spectrophotometric measurements of it are exceedingly difficult.

Instead of simply adopting a mean temperature, a better approximation is to use a power-series expansion about the mean, keeping the first few terms. This method is described by Torres-Peimbert and Peimbert (1977). It has not been widely used, partly because the determination of the coefficient representing the second-order expansion term requires more observational information than is usually available, and partly because it is not obvious that a second-order expansion is sufficient to represent the exponential temperature dependence of ε for collisionally excited lines.

Mean values of the density can be estimated, again from equation (2), from collisional deexcitation effects in ions which have observable lines from two upper levels with nearly the same excitation energy. The best examples are [O II] λ3726/λ3729, [S II] λ6731/λ6716, [Cl III] λ5538/λ5518 and [Ar IV] λ4740/λ4711. Using these mean densities and mean temperatures, relative abundances of all ions giving rise to observable lines can then be calculated from equation (2) or from the second-order power series form of equation (1).

The largest uncertainty in deriving abundances is in the correction for unseen stages of ionization. For instance, from observations of [N I], [N II], [O I], [O II], and [O III], all of which have lines in the optical region, the abundances of N°, N^+, O°, O^+ and O^{++} relative to H^+ can be determined. To determine the abundances of N and O relative to H also requires knowledge of the abundances of N^{++}, N^{+++},

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N^{++++}, O^{+++} and O^{++++}, all of which can exist in planetary nebulae. In the empirical method, the relative abundances of these stages of ionization are estimated from insights gained from photoionization theory and models. For example, since the ionization potential of O^{++} is 54.9 ev, which is very close to that of He^+, 54.4 ev, and because He^+ is so efficient in absorbing photons with energy ≥ 54.4 ev, the outer edge of the O^{+++} zone coincides with the outer edge of the He^{++} region. Consequently, the correction to the oxygen abundance for the unobserved stages of ionization O^{+++} and O^{++++} can be taken from the abundance of He^{++} (both summed over entire nebulae) in the form

$$\frac{N(O)}{N(H)} = \frac{N(O^+) + N(O^{++})}{N(H^+)} \cdot \frac{N(He^+) + N(He^{++})}{N(He^+)} . \qquad (4)$$

Similar but more complicated expressions are used to derive the abundance of N from the abundance of its one observed stage of ionization N^+, and the abundance of Ne from the abundance of Ne^{++}, if infrared observations of [Ne II] λ12.8μ are not available to give the abundance of Ne^+. These expressions are based on the similarity of the first and second ionization potentials of O, N and Ne, and hence the expected coincidence of the O^+, N^+ and Ne^+ zones, as well as of the O^{++}, N^{++} and Ne^{++} zones (Torres-Peimbert and Peimbert 1977).

Probably the best collections of spectrophotometric data and resulting abundances for planetary nebulae are the papers of Torres-Peimbert and Peimbert (1977) and Barker (1978a, b). The accurate measurements by these authors show that in the lower-ionization planetaries, a correction for He° within the H^+ zone is necessary to get high precision He abundances. Although a correction formula based on the approximate equality of the ionization potentials of He° and S^+ has been used, there are observational reasons for questioning it (Barker 1978b). Consequently the best relative helium abundances are those derived from the nebulae with hot central stars and strong He II λ4686. The general conclusions from these papers are that planetaries of widely varying kinematic properties have nearly identical (approximately solar) relative abundances of H, He, Ne and O, and less reliably, N and S. This differs from stars, in which the heavier-element abundances (metals such as Fe, Ti and V) are correlated with kinematic properties. There is some weak evidence for a galactic gradient of the relative abundances of He, O and N with respect to H, in the sense that they all decrease outward, but there is considerable scatter about the mean relationship. Accurate spectrophotometry of more ions, such as the Space Telescope can make in the ultraviolet spectral region, are clearly desirable.

Some ultraviolet measurements already exist. Although attempts to observe planetary nebulae were made with the University of Wisconsin OAO-2 satellite, no positive detections of individual emission lines were made (Code and Savage 1972). Ultraviolet spectra have been obtained with a 33-cm telescope in an Aerobee rocket of the planetary nebulae NGC 7027 (Bohlin et al. 1975) and NGC 7662 (Bohlin et al. 1978). Both

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these objects showed intense emission lines of C IV λ1549, He II λ1640 and C III] λ1908, and NGC 7662 also showed strong [Ne IV] λ2440. Several other lines were possibly detected. Although the spectrophotometric accuracy of these measurements is naturally not nearly as high as the best ground-based measurements, they give very valuable information. The high dust extinction of NGC 7027 is well confirmed by the He II λ1640/He II λ4686 ratio, and for NGC 7662 an abundance ratio N(C)/N(O) = 1.0, considerably higher than expected, was derived from a model calculation. Also, a 22-cm Cassegrain telescope in the ANS satellite has been used to detect and measure C IV λ1549 in about 10 bright planetary nebulae (Pottasch *et al* 1978a). Two interference filters centered at λ1550 were used, one approximately 50 A wide and the other 150 A wide, together with other interference-filter measurements at wavelengths away from strong lines. These observations, though relatively crude (the entrance aperture is a 2!5 square), agree with the rocket spectra in giving a considerably lower relative abundance of C than the optical determinations of Torres-Peimbert and Peimbert, which are based on weak high-level recombination lines. The difficulty with measurements of very weak lines is that if the line is not detected, it is ignored, but any noise or blending with other weak lines that may occur tends to strengthen the line and thus may introduce a positive bias. The ANS satellite measurements also produced some information on the continuous spectra of the central stars of planetary nebulae. They all showed that the indirect methods of determining stellar temperatures and ultraviolet luminosities, based on longer wavelength optical measurements, give incorrect results in some cases (Pottash *et al*. 1978b).

Very recently the IUE 45-cm Cassegrain telescope has begun to provide ultraviolet spectra of planetary nebulae. In NGC 7027 a total of 20 emission lines were measured in the wavelength range λλ1406-3000, including one or more lines of the ions C III, C IV, N III, N IV, Mg II and Mg V, all of which are unobservable in the optical and infrared spectral regions (Grewing *et al*. 1978). In NGC 7662, Lutz and Seaton (1979) have measured accurately the wavelengths of [Ne IV] λλ 2421.84, 2424.47 and from the intensity ratio of these two lines found N_e = 1.1 x 10^4 cm^{-3}, in close agreement with the value determined from the corresponding [Ar IV] doublet in the optical region. Flower *et al*. (1979) have identified ultraviolet lines of C III], C IV, N III], N IV], N V, O IV], Mg II and Si III] in the "young planetary nebula" V 1016 Cyg.

The few available rocket and satellite observations of planetary nebulae clearly show that the Space Telescope will be able to detect and make accurate measurements of planetary-nebula spectra. Using figures given by Longair (1979) and Bahcall and O'Dell (1979), it appears that the Faint Object Spectrograph with a resolution $\lambda/\delta\lambda = 10^3$ and a diaphragm 0''25 in diameter would require 1 sec exposure time to achieve a signal-to-noise ratio of 10 at Hβ surface brightness S(Hβ) = 4.3 x 10^{-12} ergs cm^{-2} sec^{-1} $(arcsec)^{-2}$. A complete list of observed Hβ surface brightnesses (averaged over the face of the nebula) is available (O'Dell 1962), and shows that the nonstellar planetary

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nebula with the brightest surface brightness, IC 418, has S(Hβ) = 2.4×10^{-12} erg cm^{-2} sec^{-1} (arcsec)$^{-2}$. This would require only 2 sec observing to obtain the signal-to-noise ratio quoted above. Several of the strongest lines in the ultraviolet are expected to be of comparable strength to Hβ and, since the sensitivity of the Faint Object Spectrograph is fairly uniform, would be observable in approximately the same exposure time. Put another way, with a limiting exposure of 10^4 sec, emission lines in IC 418 should be measureable down to about 0.002 the strength of Hβ. This will include a very large number of ultraviolet lines. There are approximately 10 northern planetary nebulae with average surface brightness comparable with that of IC 418. For a fainter nebula such as NGC 6720 with an average surface brightness approximately 100 times smaller than IC 418, a 10^4 sec exposure should detect and measure to the quoted accuracy lines down to about 0.2 the intensity of Hβ. According to available estimates, there should only be 4 or 5 lines at this strength in the satellite ultraviolet region (λλ1000-3000), but they include C III] λ1909 and C IV λ1549, which should provide important information on the C abundance. NGC 6853, another well known planetary, is down in surface brightness by another factor of 8 below NGC 6720, but C III] and C IV should still be measureable in it.

To gain additional photons on faint nebulae, the full 200μ height of the Digicon array can be used with a slit 0".25 x 1".4; this has seven times the area of the 0".25 diameter circular aperture and therefore a sensitivity correspondingly larger. This aperture is still considerably smaller than the apertures used for nearly all ground-based work on planetary nebulae to date. There is no doubt that many emission lines can be observed in the ultraviolet spectra of the brighter planetaries, and at least a few lines in many planetaries.

The great advantage of the ultraviolet spectral region is that in it many ions that do not have strong collisionally excited lines in the visible region are observable. A list of expected ultraviolet emission lines prepared some years ago shows that of the ten most abundant elements, the ions with previous ionization potential up to 90 ev that have lines in the satellite ultraviolet are C II, C III, C IV, N II*, N III, N IV, N V, O III* O IV, O V, Ne III*, Ne IV*, Mg II, Si II, Si III, Si IV, S II*, S III*, S IV, S V, Ar IV*, Ar V (Osterbrock 1963). Only the ions marked with asterisks have strong lines in the visible or near infrared.

The ultraviolet spectral region is especially valuable because there are many discrepancies between the predictions of theoretical photoionization models of planetary nebulae and the observations. In general, the calculations always indicate sharp edges to the various ionization regions so that for instance O^+, Ne^+ and N^+ all occur together in the H^+, He° zone in low-ionization planetary nebulae, and there is practically no O^{++}, Ne^{++} or N^{++} in this zone. Yet the best observational data show clearly that there is considerable penetration of O^{++} and Ne^{++}

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into the O^+, N^+ zone in IC 418, (e.g. Reay and Worswick 1979). This must be due to the complicated density fluctuations, often described as filamentary structure, that are not taken into account in the models. The careful measurements of Hawley and Miller (1977) show that in the outer part of NGC 6720 [Ne III] and [O II] are both strong in the same region, a result which contradicts the available photoionization models and the conventional procedure for correcting the Ne abundance for unobserved Ne^+. Here it seems likely that the highly efficient charge-transfer process between O^{++} and H° (Butler *et al.* 1979) significantly reduces the equilibrium fraction of $N(O^{++})/N(O^+)$ in the outer part of the region where photons that can ionize O^+ are available. The ultraviolet measurements of other ions can be used in place of other perhaps equally invalid corrections for unseen stages of ionization.

The ultraviolet spectral region contains significant additional information on the temperature within nebulae, because it extends the range of excitation energy that can be observed. Thus the temperature-sensitive [O III] ratio [I(λ5007) + I(λ4959)]/I(λ4363) can be supplemented by O III] I(λ1661) + I(λ1666) which arise from the ^5S level at an excitation potential of 7.45 ev. Similarly the [N II] ratio can be supplemented by I(λ2140) + I(λ2143) arising from the corresponding ^5S level at 5.79 ev. Other ions with temperature-sensitive ratio in or including the ultraviolet are [Ne III] [I(λ3967) + I(λ3869)]/I(λ3342) (much better observed from space than from the ground), Si II I(λ2335)/I(λ1817), and [Mg V] [I(λ2786) + I(λ2931)]/I(λ2415). Ratios that are sensitive to both temperature and density include Si III] λ1892/λ1206 and C III] λ1907/λ1909. In all cases the best way of using the observational data is to compare with a model, but if this is impossible the mean temperatures and densities derived from these ratios can be used to estimate the abundances of all observed ions.

Bright planetary nebulae such as IC 418 typically have sizes of order 10", while lower surface brightness nebulae such as NGC 6720 and NGC 6853 are several minutes of arc in diameter. With either a 0″.25 circular aperture or a 0″.25 x 1″.4 slit it will be possible to sample over the face of the nebula in a systematic way, rather than observing the whole nebula, or a slice through it, as has often been done in the past with ground-based telescopes. The importance of adequate finding and guiding systems cannot be overemphasized.

Besides the Faint Object Spectrograph, the Faint Object Camera can be used in the spectroscopic mode with a long slit, 10" x 0″.1, with 0″.1 resolution along the slit. Operated in this way, it has to have a resolution $\lambda/\delta\lambda = 2 \times 10^3$ but a limiting magnitude on point sources 3.4 magnitudes brighter than the FOS. This presumably means that for the same exposure time it will only detect lines in nebulae that are about 20 times brighter than the faintest detectable with the FOS used with an 0″.25 aperture. This still permits measurement of many of the brighter planetaries. Compared with the FOS used with a 0″.25 x 1″.4 slit, the FOC spectrograph is slower by a factor of about 140, but provides seven different 0″.1 x 1″.4 areas along the slit. The fact that the

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wavelength regions $\lambda2700 < \lambda < \lambda3600$ and $\lambda > \lambda5400$ are unobservable with the FOC spectrograph is a severe limitation.

All observed planetary nebulae contain inhomogeneities in density on a small scale: filaments, condensations, bright knots, and the like. As Aller (1976) has particularly emphasized, they must be taken into account in any complete model. With the Space Telescope's very good angular resolution, it will be possible in many cases to get spectra of individual knots or fronts, contaminated only by the foreground and background emission in the nebulae. In these as in all other spectroscopic measurements of planetary nebulae with the Space Telescope, not only the ultraviolet emission lines, but the optical and near infrared lines out to the limit of sensitivity at λ9000 should be measured. Attempting to combine them with ground-based optical data, which inevitably have been or will be taken with lower spatial resolution and different guiding, would seriously degrade the results.

In this connection, the direct camera, operated in the Wide-Field mode at f/13, will be particularly valuable for investigating the ionization structure of planetary nebulae. Several of the special line filters that "may be available" will be especially suited for this program: [O I] λ6300, Hα, [O II] λ3727, [O III] λ5007, [Ne III] λ3870, and in the ultraviolet C IV λ1549 and Lα. Exposure times used by Minkowski (1968) with the Hale telescope at f/3.7 ensure that the first five of these filters will certainly provide data for some of the brighter planetaries in reasonable exposure times, and the two ultraviolet lines are expected to be of comparable brightness. These line-filter direct images will be useful not only for studying the overall ionization structure of a nebula, but particularly to see how the ionization varies in, around, and behind small dense condensations. Comparison of the [O III] and [Ne III] images will be especially valuable in studying the effects of the O^{++} + H charge-transfer reaction on the $O^{+} \rightleftarrows O^{++}$ ionization equilibrium. The He I λ10830 filter will be useful in assessing the effects of colisional excitation from the He I 2 ^3S metastable level. It is a strong line and images of the bright nebulae will be obtainable with it if the CCD sensitivity holds up to 1.08μ, as it should.

Finally, the High Resolution Spectrometer on the Space Telescope will be extremely useful for studying the line profile of Lα in planetary nebulae. Forbidden lines and recombination lines to excited upper levels (except He° 2 ^3S) are not subject to radiative transfer effects because of the very small optical depths in all these lines. However, Lα is the opposite extreme with an estimated optical depth up to 10^4 at line center in an object with small expansion velocity. The problem of the transfer and escape of resonance-line photons in a gaseous nebula has been theoretically investigated in great detail. Each treatment makes highly specific predictions, about the emergent line profile at each point on the surface of the nebula. The resolution $\lambda/\delta\lambda = 2 \times 10^4$ or $\delta\lambda = 0.06$ A corresponding to 15 km s^{-1} should be ideal for testing these predictions observationally. Since

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Lα is expected to be of order 10 times stronger than Hα in slightly reddened planetaries, there should be no problem observing the brighter planetaries with a 1" x 1" or 2" x 2" entrance aperture.

H II REGIONS

H II regions are spectroscopically similar to planetary nebulae, since both are photoionized, low-density gas clouds. However, H II regions represent samples of interstellar matter from which stars have recently formed, and thus provide the opportunity for measuring abundances in material quite different from planetary nebulae. In general, H II regions are less regular in form than typical planetary nebulae. The gas in H II regions is usually not symmetrically distributed around one central star, but more often is chaotically distributed about several O stars which contribute to the ionization. Hence, realistic models are more difficult to calculate, and the results on the ionization structure calculated from necessarily simplified models must be regarded more as a guide than as a standard that can be directly compared with observations. The importance of using the Space Telescope to observe all relevant stages of ionization is again obvious.

A large amount of optical spectrophotometric data exists in published form and has been summarized by Kaler (1976) and Alloin *et al*. (1978). The Orion Nebula, NGC 1976, has been studied in most detail (Peimbert and Torres-Peimbert 1977), and shows essentially solar abundances of the light observable elements. Several other more distant H II regions have been carefully observed and appear to show a galactic abundance gradient in which the relative abundances of N and O decrease outward, N having the steeper and better determined gradient (Peimbert *et al*. 1978, Hawley 1978). The ionization is lower in typical H II regions than in typical planetaries, but close to the O6 star θ Ori A in NGC 1976 the level of ionization is comparable to that in many planetaries.

The Faint Object Spectrograph, with a slit 0".25 x 1".4, will be most useful for measuring emission lines in H II regions. The brightest areas near the center of NGC 1976 have Hβ surface brightness only about a factor of 2 lower than IC 418, while the outer parts are down by a factor of 10^2 or more from this value (Dopita *et al*. 1975). Of the northern H II regions, only M 8 has a surface brightness even comparable with NGC 1976, and in general the exposure times will be long, even with the large slit.

Density fluctuations are very important in H II regions, and spectra of some of the fronts and knots in NGC 1976 should yield good comparisons with theoretical predictions of the structure and ionization stratification of ionization fronts and globules. Very small condensations recently identified by Laques and Vidal (1979) will be particularly interesting to study in the ultraviolet spectral region. Line-filter direct images with the very good angular resolution of the Faint Object

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Table I

Ion	i, j	⟨Ω(i, j; T)⟩				
	T	5000	10000	15000	20000	Reference
C II]	$2p\ {}^2P^0$, $2p^2\ {}^4P$	3.24	3.17	3.09	2.97	Jackson 1973
C III]	$2s^2\ {}^1S$, $2p\ {}^3P^0$	1.45	1.44	1.42	1.41	Flower and Launay 1973
C III	$2s^2\ {}^1S$, $2p\ {}^1P^0$	2.80	2.86	2.92	2.92	Flower and Launay 1973
C IV	$2s\ {}^2S$, $2p\ {}^2P^0$	8.50	8.66	8.73	8.80	Bely 1966*
N II]	$2p^2\ {}^3P$, $2p^3\ {}^5S^0$	1.27	1.28	1.29	1.27	Jackson 1973
N III]	$2p\ {}^2P^0$, $2p^2\ {}^4P$	1.86	1.91	1.89	1.83	Jackson 1973
N IV]	$2s^2\ {}^1S$, $2p\ {}^3P^0$	0.83	0.82	0.82	0.81	Osterbrock 1970*
N V	$2s\ {}^2S$, $2p\ {}^2P^0$	6.61	6.65	6.69	6.72	VanWyngaarden and Henry 1976
O III]	$2p^2\ {}^3P$, $2p^3\ {}^5S^0$	1.23	1.34	1.36	1.35	Jackson 1973
O IV]	$2p\ {}^2P^0$, $2p^2\ {}^4P$	1.33	1.37	1.42	1.44	Extrapolated*
O V]	$2s^2\ {}^1S$, $2p\ {}^3P^0$	0.52	0.51	0.51	0.51	Malinovsky 1975*
O VI	$2s\ {}^2S$, $2p\ {}^2P^0$	4.98	5.00	5.03	5.05	Bely 1966*
[Ne II]	$2p^5\ {}^2P^0_{\frac{3}{2}}$ $2p^5\ {}^2P^0_{\frac{1}{2}}$	0.36	0.37	0.37	0.38	Seaton 1975
[Ne III]	$2p^4\ {}^3P$, $2p^4\ {}^1D$	1.35	1.34	1.33	1.32	Pradhan 1974
[Ne III]	$2p^4\ {}^3P$, $2p^4\ {}^1S$	0.15	0.15	0.15	0.16	Pradhan 1974
[Ne IV]	$2p^3\ {}^4S^0$, $2p^3\ {}^2D^0$	1.12	1.13	1.14	1.15	Lutz and Seaton 1979
[Ne V]	$2p^2\ {}^3P$, $2p^2\ {}^1D$	2.16	2.12	2.08	2.05	Giles 1979
[Ne V]	$2p^2\ {}^3P$, $2p^2\ {}^1S$	0.32	0.28	0.27	0.27	Giles 1979
Mg II	$2s\ {}^2S$, $2p\ {}^2P^0$	17.2	18.5	19.6	20.5	Burke and Moores 1968
Si III]	$3s^2\ {}^1S$, $3p\ {}^3P^0$	2.8	2.8	2.8	2.7	Osterbrock and Wallace 1977
Si IV	$3s\ {}^2S$, $3p\ {}^2P^0$	16.9	17.0	17.0	17.1	Flower and Nussbaumer
S VI	$3s\ {}^2S$, $3p\ {}^2P^0$	11.8	11.9	11.9	11.9	Flower and Nussbaumer 1975

*See Osterbrock and Wallace 1977

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Camera, particularly in Hα, [O II], [O III], [Ne III], and Lα will undoubtedly reveal previously unknown, even smaller condensations. Though a long exposure will be required, it will be extremely informative to get profiles of Lα in the brightest parts of NGC 1976 with the High Resolution Spectrograph. The optical depth there is probably higher than in most bright planetaries so that the resonance-line radiative transfer theories will be more severely tested.

The Space Telescope observational data will be valuable in understanding the structure and content of H II regions and planetary nebula. Large amounts of money, time and effort will go into obtaining the data. Comparable amounts of money, time and effort should go into interpreting it. Realistic models must be calculated and their physical parameters must be adjusted until they agree with all the observational data. Atomic data, particularly the collision strengths for all likely lines of all stages of ionization, should be calculated and available. In Table I some of the best values of the most important collision strengths, chiefly for ultraviolet lines but including some optical and even one far infrared line, are collected. With modern techniques, it is possible to calculate collision strengths to an accuracy better than ten percent (Giles 1979). It will be important to invest the necessary computing resources to obtain collision strengths for the many important lines of the third row of the periodic table before the Space Telescope data begin coming down.

The properties of the photoionizing star or stars are important for any model. The best possible stellar models must be calculated and used in the nebular models (Balick and Sneden 1976, Hawley and Grandi 1977, Shields 1978). The effects of dust on the ionizing radiation and on the emitted lines must be correctly taken into account, including not only true absorption but also scattering, and the assumed properties of the dust must be systematically varied. Also, the line-transfer problem must be treated correctly, for not only Lα but also the reasonance lines of C IV, N V, O VI and many other ions have large optical depths in a typical planetary nebula or H II region. In the gas itself, density inhomogeneities and internal velocities must be taken into account, as emphasized above. A reasonably correct description of the true physical situation, although complicated and expensive, will be necessary to extract the full value of the Space Telescope nebular data.

SUPERNOVA REMNANTS

In old supernova remnants, such as the Cygnus Loop, mechanical energy is converted into heat in a shock wave running out through the surrounding interstellar gas and is radiated, partly in the form of emission lines. In some young remnants, such as Cas A, fast moving gas clouds with very anomalous abundances, evidently ejected by the supernova itself, can be observed. The Crab Nebula, approximately 10^3 yr old, is a case in which we observe gas enriched in He but not significantly in heavier elements, photoionized by the optical synchrotron radiation from the central part of the remnant. In these and in all supernova

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remnants, observations of more ions in the ultraviolet spectral region will clearly help delineate the physical conditions and abundances better than the presently available optical data alone can do. They are faint objects, but available optical data suggest that the brighter ultraviolet lines will be measureable in several of them with the Faint Object Spectrograph, although interstellar reddening will be a severe problem in Cas A. The high angular resolution of the space telescope will be very useful because of the many small knots, condensations and filaments, and the generally highly irregular structure of supernova remnants.

In the shock-wave remnants, high temperatures are reached, up to approximately 2 x 10^6 K in Cygnus Loop, for example. X-rays have been detected from several remnants, and optical [Fe XIV] λ5303 emission from at least two (Danziger and Dennefield 1976, Woodgate et al. 1977). The ionization is collisional, and decays as the temperature falls, as a consequence of radiative cooling behing the shock. Some of the temperature-sensitive lines mentioned above and others from even higher excitabion levels will be useful to test these calculations. Shemansky et al. (1979) have detected several ultraviolet lines in the Cygnus Loop, including C II λ1037 and C III λ977, using a spectrometer in Voyager 2.

Large numbers of simplified models have been calculated by Dopita (1977) and Raymond (1979); they discuss in detail which lines are most useful for abundance determinations, and which for determinations of the physical parameters such as density and shock velocity. Observed deviations from the symmetric plane-parallel shocks of these theoretical treatments clearly are large, no doubt because of the inhomogeneous structure of the ambient interstellar gas clouds. More realistic models and interpolation schemes based on them are needed; probably observations on as small a linear scale as possible will most closely match the uniform conditions of existing models.

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DISCUSSION

Collin-Souffrain (Discussion leader): I want only to mention briefly some particular points concerning the observations of Planetary nebulae and H II regions that can be made with the ST. There are many other possibilities and I am sure that some of them will be raised in the following discussion.

Dr. Osterbrock has emphasized the importance of knowledge of the ionization structure and of the detailed morphology of ionized regions, in order to obtain a better understanding of their physics. He mentioned in particular that the presence of density inhomogeneities may be important for the whole nebular spectrum. These studies are also important from the standpoint of their formation and evolution.

With regard first to the planetary nebulae, small condensations have been observed in the nearest example, the Helix nebula. They are about one arcsec in diameter and are of high surface brightness. Their detailed study is particularly well suited for observation using the FOC with interference filters. It is most probable that such globules are present in many planetary nebulae and it will be important to detect them and measure their line intensities - even with no spatial resolution.

The study of young or proto-planetary nebulae should also be a goal for the ST. Such objects have already been studied in the UV range by Flower and coworkers and have revealed a very rich spectrum. They have typical dimensions of a few arcsec. The ST will enable their density distribution to be determined, which, at the present time, is a very controversial problem: does it increase or decrease towards the edge of the nebulae? Are the shells single or multiple? Clearly answers to these questions will lead to a considerable improvement of our knowledge of the formation processes of planetary nebulae, of their duration, of their stellar winds, etc.

Dust in planetary nebulae is also a very important problem both for its great influence on the overall nebular spectrum and from the point of view of its physics: how does it form, how is it destroyed? These problems can be attacked successfully with the ST because of its capability of measuring directly the intensity of the UV band at λ 2200 Å. On the other hand recent UV observations of the MgII (λ 2800 Å) lines have shown that they are more than an order of magnitude fainter than the predictions of photoionization models while the MgV line, which is produced in the inner part of the nebula, is normal. Is this due to a deficiency of magnesium which at the edge of the nebula is locked in dust grains? Or is it due to destruction of the resonant photons by dust? Whatever the right explanation it will give important clues to the problem of the presence and of the geometry of dust inside NGC 7027. One can even imagine a possible test for the absorption of photons, by

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looking at monochromatic images in the MgII lines: if the photons diffuse and are absorbed in a peripheral Mg^+ - H^o region, the Mg II image should be slightly larger than, for instance, the [OII] image.

Finally an improvement of our knowledge of the physical processes in general can be obtained by a systematic confrontation between the most elaborate models and the finest observations. In this respect, I would like to mention the work of Pequignot and coworkers, who from detailed photoionization models of NGC 7027, have shown that the only way to explain the discrepancy between the computed and observed intensities of some low excitation lines, was to assume high rates of charge exchange processes. In particular, they found that the reaction $O^{++} + H^o \rightarrow O^+ + H^+$ was very fast. At that time, atomic physicists considered this reaction was of negligible importance. But recently, as mentioned by Dr. Osterbrock, Butler et al. re-evaluated this rate and found a value which is in agreement with the earlier empirical estimate of Pequignot et al. One should note that this kind of work was only possible because very detailed spectroscopic observations, in particular by Kaler et al. were available. It is thus quite probable that new UV observations will lead to the empirical discovery of new physical processes. Of course, all previous models of planetary nebulae as well as models of active galactic nuclei have now to be reconsidered.

Concerning H II regions, Dr. Osterbrock has clearly shown how complex a picture is now emerging with globules, ionization fronts, and even dense shocked shells. H II regions are often located at the edge of molecular clouds, forming a kind of "blister", as Israel called them. Dynamical models have been developed for these structures by Tenorio Tagle called "champagne models". Dyson, on the other hand, has studied the interaction of stellar winds with interstellar matter - these two theories account for the presence of thin dense shells of material, and in some H II regions, shell structures, with thickness less than 1 pc, have been observed in the [OIII] lines and are probably common features in H II regions. The high spatial resolution of the ST will help detect new examples of such structures and give better understanding of their dynamics, although unfortunately the spectral resolution is not sufficient to give directly a picture of their velocity structure.

As mentioned by Dr. Osterbrock, high excitation globules, not spatially resolved from the ground, have been observed by Vidal and Laques in the Orion nebula, and their nature is as yet completely unknown: are they clumps in the process of condensation by thermal or gravitational instability or relics of the primordial HI region? And, above all, are such globules common features in HII regions? These questions could be answered with the ST.

Stasinska has shown that large uncertainties in the interpretation of line intensities can result from an absence of knowledge of the

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structure of H II regions and of their inhomogeneity. For instance, the empirical methods of determining the ionization correction factors are not accurate when the distribution is inhomogeneous, and large errors in the deduced abundance of sulphur and even of oxygen can be made. Helium abundances could also be wrong by 10 or 20%, which is an important uncertainty for this element. On the other hand, the method based on temperature fluctuations developed by Peimbert and Costero (1969) fails in the case of a large abundance of oxygen (2 or 3 times the solar value) which leads through radiative losses in the infrared OIII line to very large temperature variations within the HII region. Even with elaborate models, it is impossible to deduce the oxygen and nitrogen abundances (as soon as they are greater than the solar values), with an accuracy better than a factor 3, if the structure of the H II region is not known!

In this context, studies of bright extragalactic H II regions should be an important goal of the ST. Indeed, our knowledge of H II regions in the galaxy is limited, in the optical and UV range, to the vicinity of the Sun, and to the anticenter direction. There are strong indications however that HII regions near the center of spiral galaxies, have large abundances of C, N and O, and this, of course, is important for galactic chemical evolution, in particular. In order to get better information on these regions, it will be important to get an idea not only of the density distributions of the material in it, but also of the spatial distribution of some strong lines: for instance Stasinska has shown that overabundant regions should be characterized by a very weak ratio $\frac{[\mathrm{O\ III}]\ 5007 + 4959}{\mathrm{HeI}\ 5876}$ in the center, and a strong increase of this ratio outwards.

Finally, I would like to stress the possibility of using the ST for studies of novae in their nebular stage. As for HII regions and planetary nebulae, the abundances of elements can be obtained through the study of their nebular spectra and very large abundances of CNO have been found in this way. Nitrogen, for instance, is generally overabundant by a factor 100 and since it is generally in the form of highly ionized species (N^{+5}, N^{+4}) which are only observable in the UV range, the ST will be of great significance.

When the nebular shell expands and becomes spatially resolved, it is possible to deduce the distance of the nova by comparing the radial and expansion velocities. Presently this has been performed only for very few nearby novae, since the surface brightness of the shell decreases with time. The ST, allowing spatial resolution at the beginning of the nebular phase, could lead to a considerable increase in the sample of novae having known distances.

On the other hand, when the spatial resolution is not sufficient to

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distinguish the nebular shell, the nebular spectrum itself is very difficult to isolate and interpret, since the spectrum is a mixture of several components (the stellar remnant, the accretion disk and the ejected shell), and also because the shell itself is largely inhomogeneous. Recently Williams et al. have obtained for the first time a spectrum of different parts of the old nova Her 34 and they have shown that the shell is composed of 2 "polar" caps and one "equatorial" ring, having different physical conditions and different abundances. Clearly, such studies, which are well suited for the ST, would be of great interest for our understanding of the nova phenomenon.

I would like to end by recalling that all these proposals for the use of the ST are made on the basis of our present state of knowledge of HII regions and planetary nebulae. Because of the large increase in spatial resolution and spectral range that the ST will achieve, it is highly probable that unexpected new problems will be raised and also that we will be obliged to correct misinterpretations of the previous observations.

Burbidge: Which are the elements observed in planetary nebulae that indicate abundance gradients across the disk of the galaxy?

Peimbert: The evidence is reasonably good for a decrease with galactocentric distance of the N/H, O/H and He/H abundance ratios.

Burke: With respect to units, it might be useful to remember that a flux of 4×10^{-12} erg cm^{-2} s^{-1} at wavelength 2500 Å corresponds to a spectral flux density of about half a millijansky.

Gallagher: I will give three examples of how UV observations with ST can provide important information on time-dependent phenomena in galactic novae. First, novae form dust and we are able to observe them from the earliest stages when there is no dust at all to the later stages when a strong infrared excess is observed. Observations throughout that period give direct information about the nucleation process. Novae are often relatively faint during the critical early phase when the dust is forming. ST will enable them to be studied with high spectral and spatial resolution so that we can see where the dust is forming. Second, the emission lines observed in old nova shells differ from those in the shells of planetary nebulae because the source of UV radiation has switched off. The optical emission lines observed come from high levels and might be pumped by various fluorescent mechanisms. Consequently, there are problems in interpreting the optical emission lines to determine relative abundances which are relevant tests of hydrogen flashes and white dwarfs. In the UV, ground state transitions enable some of these difficulties to be avoided to some extent. Third, the energy shift that occurs after a nova goes off is a very sensitive test of the mass of the white dwarf involved

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and provides a direct test of the nuclear runaway theory. By understanding how novae evolve in the UV where their evolution tends to be flatter, it may be possible to make better use of them as distance indicators.

Peimbert: HII regions show a very strong continuum due to dust-scattered light in the 1000 to 3000 Å range. IUE observations, in the low dispersion mode, of HII regions in the solar neighbourhood show only a continuous spectrum with the exception of the Orion nebula where λλ 1909 CIII, 2326 CII, and 2470 [OII] have been detected. Observations at higher dispersion will increase the emission line to continuum ratio and therefore a faster instrument with higher dispersion will allow the study of a larger number of emission lines in galactic HII regions.

Two effects make the detection of emission lines in giant HII regions with high heavy element abundances more difficult than in giant HII regions with low heavy element abundances: (a) their higher dust content produces, in general, a brighter continuum due to dust-scattered light and (b) their lower electron temperatures make the collisional excitation of UV lines less likely. For galaxies at a few Mpc from us, the ST will enable us to select areas of HII regions without projected O stars and thus suppress the intensity of the UV continuum. The study of these HII regions will increase significantly our knowledge of abundance gradients, particularly that of C/H, in spiral galaxies.

The observation of the planetary nebulae in the Magellanic Clouds with the ST is of great interest for the following reasons: (a) the heavy element content of the interstellar medium in the Clouds is different from that of the solar neighbourhood and therefore abundance determinations from planetary nebulae will provide constraints for evolutionary models of intermediate mass stars with different heavy element content. (b) The expected diameters of the brighter planetary nebulae in the Clouds are several tenths of arcsec, which is well within the resolution range of ST. From the diameters, the known distance and the observed Balmer fluxes it will be possible to derive the root mean square masses for the planetary nebulae in the Magellanic Clouds; in our galaxy, with the exception of two or three objects, we do not know the distances and consequently the masses of the shells of planetary nebulae. (c) The masses, fluxes, densities and ionization distribution will enable us to establish a reliable scale for planetary nebulae in our galaxy.

Field: The presence of dust in gaseous nebulae has been mentioned by several speakers. Can we say something more about it?

Peimbert: In addition to dust scattered light in HII regions, the 2175 Å absorption feature is evident in planetary nebulae and HII regions. In particular this feature has been detected, by our group and other groups, in IC 418, the Orion nebula and M8. May I ask

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Dr. Bohlin if he thinks that the increase with distance to the Trapezium of the λ 2175 Å feature indicates graphite destruction in the central regions of the Orion nebula?

Bohlin: Bohlin and Stecher (BAAS - Dec. 1975) have a long slit rocket spectrogram in the Orion region from 1200 - 2800 Å. The resolution is ∿ 20 arcsec spatially and 15 Å spectrally. θ^2 Ori B is in the slit and the rocket has been calibrated on the IUE scale using the IUE spectra of θ^2 Ori B obtained by Bohlin & Savage. The ratio Ori Neb/θ^1 Ori C as a function of distance is being interpreted theoretically by Adolf Witt. The θ^1 Ori C spectrum is from IUE, also. Initial results indicate that the dust in Orion is similar to other results by Witt in terms of albedo $a(\lambda)$ and scattering parameter $g(\lambda)$. Because of these complications and that of geometry, it seems unlikely that anything useful can be said about the grain size distribution with distance using the reflection of continuum light from the dust. A more fruitful approach to answering this question is being pursued by Bohlin and Savage, who are producing reddening curves for the 4 Trapezium Stars and θ^2 Ori A and B.

Snow: I can readily think of two aspects of grains that can be explored with the ST:

1. The High Speed Photometer will have the capability of measuring polarization in the ultraviolet, and to date nothing is known about whether or not the interstellar grains create ultraviolet polarization. Hence the ST will provide the first opportunity to explore this and, especially if polarization is found, will produce a wealth of new information about the optical properties of the grains. This will be especially interesting for the extinction bump at 2200Å.

2. There are now specific predictions of structure in the ultraviolet extinction curve due to molecular solids in grain mantles. Any such structure will be best observed in very heavily reddened lines of sight, and ST will allow significant progress in this direction, particularly in the ultraviolet.

Petrosian: I would like to remark on the effects of dust which complicate the simple picture described by Dr. Osterbrock. The dust grains in the nebulae (if any), through absorption and scattering of the ionizing radiation, can modify the ionization structure of nebulae. Only minor modifications are expected if the optical properties of the grains do not vary with frequency. Large effects are expected if the optical properties (such as absorption and scattering opacities and albedo) of the grains vary rapidly with frequency beyond the Lyman limit. This frequency range is not accessible to direct observation so that very little is known about grain properties in this frequency range. Furthermore, calculation of the effects of dust on line intensities is in general complicated because one is normally dealing with dust optical

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depths of order unity where simple approximate solutions to the equation of radiative transfer are not possible.

Nevertheless for a given grain model one can calculate their expected line intensities. Hopefully, comparison of this with observations of a sufficient number of UV lines by the ST and IR lines from ground based instruments one can say something about the optical properties of grains in this otherwise inaccessible range of frequencies.

Heidmann: In collaboration with Bottinelli, Gouguenheim, Casini, Tarenghi and Benvenuti, we have discovered in some galaxies supergiant HII regions which each are 100 times larger than giant HII regions of the type of NGC 604 in M33 or 30 Doradus in the LMC. This is the case in several respects: they are 100 times more luminous intrinsically, their masses may reach 10^8 ⊙, their UV intrinsic luminosity at 1550 Å is 100 times that of 30 Doradus and they contain as many as 10^4 O or B stars. They are an interesting extension of HII regions towards the gigantic end in the investigation of ionized gaseous nebulae. Their typical sizes are around one arcsec which makes them of particular interest for study with ST. (cf. Casini and Heidmann in ESA/ESO Workshop on the Astronomical Uses of the ST, Geneva, 1979).

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