PHYSICAL PROCESSES IN NEBULAR SHELLS AND THE INTERPRETATION OF NEBULAR SPECTRA

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ABSTRACT

Computed models are now recognized as useful tools for interpretation of the spectra of planetary nebulae. However, even the most detailed models need geometrical parameters such as filling factors which are poorly determined by observations. Some effects may be seen more clearly by modeling the stratification than by just using total fluxes. A simple model for NGC 6720 is presented which reproduces the behavior of [Ne III] λ3869 observed by Hawley and Miller (1977), clearly showing the effects of charge transfer. The behavior of C II λ4267 remains puzzling. Finally, we comment on the interaction of high velocity stellar winds with nebular shells. Non-equilibrium particle distributions at the contact between the shocked stellar wind and the nebula may result in the rapid cooling of the shocked gas.

1. USES AND LIMITATIONS OF NEBULAR MODELS

In the five years since the Ithaca Symposium on planetary nebulae we have seen a major increase in the use of computed models for the interpretation of nebular spectra. One reason for this trend is the realization that such models are the best way to obtain correction factors for the unobserved stages of ionization. Models also provide representative electron temperatures needed to derive the ionic concentrations for the inner zones of high excitation nebulae for which we lack temperature sensitive line ratios. This is of particular importance in the analysis of the ultraviolet data from the IUE satellite, which has had a revolutionary impact on the study of nebular abundances.

The most extensive program has been carried out by Aller and various co-workers. Aller and Czyzak (1982) have summarized results for 41 nebulae. The method of construction of their models is set out in Keyes and Aller (1978). The parameters which are varied to fit the observed nebular spectrum are (i) the chemical composition, (ii) the density, (iii) the stellar spectrum, which can be based on model atmosphere calculations, but which may include ad hoc modifications, and (iv) the optical depth in the Lyman continuum, which they express as the ratio of

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the outer radius of the nebula to the radius of a complete Stromgrem sphere.

These models may fit the observed spectrum only approximately, especially when ultraviolet data is included. Thus, in the method described by Shields et. al. (1981), the chemical composition of the best model is not regarded as the final result. Rather, the temperature structure of the model permits the calculation of mean temperatures weighted by the various ions, and these mean temperatures are used to deduce ionic concentrations directly from the observed features. Then the ionization structure of the model provides the corrections for the ions without observed lines and the chemical abundances are found. For many nebulae, this is probably the best approach now available for abundance determinations. The results show the wonderful diversity of these objects. It is no longer possible to speak of "the mean chemical composition of planetary nebulae".

I have been involved in some attempts to model particular nebulae in great detail (Bohlin, Harrington and Stecher, 1978; Harrington *et. al.*, 1982; Harrington and Feibelman, 1983). It is not suggested that such models are feasible or even desirable for most planetaries. The primary aim is to attain some assurance that our procedures are sound and that we really are modeling the physical processes in the gas. For it must be emphasized that not only the stellar flux, but also the geometrical structure of the nebula, which is usually treated in a schematic fashon, can have an enormous influence on the predicted spectrum

In our "new, improved" model of NGC 7662 (Harrington *et. al.*, 1982) the stellar flux is not arbitrary but is interpolated directly from the model atmosphere sequence of Hummer and Mihalas (1970). The absolute flux level (i.e., stellar radius) is determined by matching the UV continuum as deduced from our IUE observations.

For this model of NGC 7662 (and also for the model of IC 3568 by Harrington and Feibelman, 1983) the density distribution was chosen so that the emissivity of the gas would reproduce observed isophotes. With knowledge of the distance, this fixes the distribution of the gas about the star, and hence the dilution of the radiation at each point. However, in both cases, the density obtained is below that indicated by density sensitive line ratios. It seems that there is small scale structure in these nebulae. We can simulate this by the use of a filling factor so that the density in the filled volume is higher while the average emissivity per unit volume remains the same.

It is also important to determine to what extent structure exists on a larger scale, that is, to what extent there is "clumping" on a scale such that the Lyman continuum optical depth of the nebula varies significantly along different radial directions. Of course we can observe such clumping in many nebulae, but in others it must exist below our limit of resolution.

We used both a filling factor and a clumping factor for the outer zone of our final model of NGC 7662. The ionic concentration of C^{+3} is obtained from the C III λ2297 recombination line, which indicates that internal dust has reduced the flux in the C IV λ1549 resonance line by a factor of 3. For nebulae where λ2297 cannot be observed, it would seem advisable to set the ionization structure by N III] λ1750 and N IV] λ1487 rather than C III] λ1909 and C IV λ1549. This model gives a good fit to almost all the observed spectral features in both optical and UV wavelengths.

But the point I wish to make here is that even when we have based the density distribution of the model on observed isophotes, we have had to use filling and clumping factors which, reasonable though they are, are nevertheless not well determined by observations. And this makes the model less compelling as a unique representation of the physical state of the gas. Pequignot (1980) pointed out, correctly, that an optically thick nebula like NGC 7027 is a better test of the theory than an optically thin one like NGC 7662, for in an optically thick nebula all radial directions terminate in an ionization front and the "clumping" parameter is of diminished importance.

We conclude that by using our current arsenal of physical processes models can be made to match the observed nebular fluxes, but that it is still hard to be positive that we have not used some stellar or geometrical free parameter to compensate for inadaquate physics. So we ask if there is any approach which can sharpen the comparison between observation and theory.

2. STRATIFICATION EFFECTS: NGC 6720

In some cases we can apply more constraints by trying to match not the integrated spectrum, but the spectrum as it varies from point to point in a stratified object. An excellent example is provided by observations of the Ring Nebula, NGC 6720, by Hawley and Miller (1977). They observed regions with greatly differing [N II] and [O II] line strengths and showed that the much used ionization correction formula, $N(N^+)/N(O^+) = N(N)/N(O)$, was valid because it gave the same nitrogen abundance in all regions of the nebula. But they were surprised by the behavior of [Ne III] λ3869. Although the ionization potential of Ne$^+$ is higher than that of O$^+$, the [Ne III] line remained strong out to the edge of the nebula while [O III] faded and was replaced by [O II] and [O I]. It has subsequently been suggested by several authors (e.g., Barker, 1980) that this is due to the effects of charge transfer from hydrogen.

I would like to present a simple model of NGC 6720 to demonstrate that this is quantitatively correct. The nebula is represented by a spherical shell with a constant density of N_H = 800 cm^{-3}. The central star is represented by model atmosphere No. 202 of Hummer and Mihalas (1970) with T_{eff}= 150,000K and log g = 7. The abundances of C, N, O, and Ne relative to hydrogen are 3.9(-4), 2.0(-4), 7.0(-4) and 1.5(-4), respectively. The stellar luminosity is set at 245 $L_\odot$ ($R_* = .023\ R_\odot$) so that the outer boundry of the model is the edge of the Stromgren sphere. The computer program and atomic parameters used for the calculation are the same as those given by Harrington et. al. (1982). Because of the high stellar temperature and large dilution factor, there is a great deal of neutral hydrogen and charge transfer is extremely effective. The table gives the integrated fluxes from this model for some of the stronger lines. Note the great strength of [O II], [N II], [O I] and [N I].

Ion	λ(A)	I(λ) (Hβ = 100)
He II	4686	30.
C II]	2328	190.
C III]	1909	250.
C IV	1549	50.
[N I]	5200	13.
[N II]	6584	690.
[O I]	6300	60.
[O II]	3727	980.
[O III]	5007	1730.
[Ne III]	3869	230.

Figure 1 shows the emissivity of some of the lines relative to Hβ as a function of radial distance. The effect observed by Hawley and Miller is striking as the [O III] line fades but the [Ne III] line actually increases toward the edge. The effect might be regarded more properly as an [O III] anomaly because in the absence of the $O^{+2} + H^0 \rightarrow O^+ + H^+$ charge transfer process, [O III] would persist to the edge the same as [Ne III] does. The behavior of nitrogen is like that of oxygen because the $N^{+2} + H^0 \rightarrow N^+ + H^+$ rate is also large, while the $Ne^{+2} + H^0 \rightarrow Ne^+ + H^+$ rate is very small. The Ring Nebula seems to be an ideal object to explore these effects and should repay more refined modeling coupled with more extensive observational mapping. But this simple model is enough to demonstrate the reality of charge transfer effects in nebulae more forcefully than modeling the integrated fluxes can.

3. THE C II λ4267 LINE

While we have a good grasp of some stratification effects, observations by Barker (1982) of the same nebula are equally effective in displaying behavior which we do not yet understand. Barker made IUE observations of the Ring at the same positions studied by Hawley and Miller, and also obtained optical observations of the faint C II λ4267 line. From the IUE observations of C II], C III], and C IV he found essentially the same carbon abundance at all positions, C/H = 3.9(-4). Now the C II λ4267 line has been considered a recombination line and used to deduce the abundance of C^{+2} ions. Barker found that in this nebula, the λ4267 line implied abundances up to 10 times higher than those obtained from C III] λ1909,

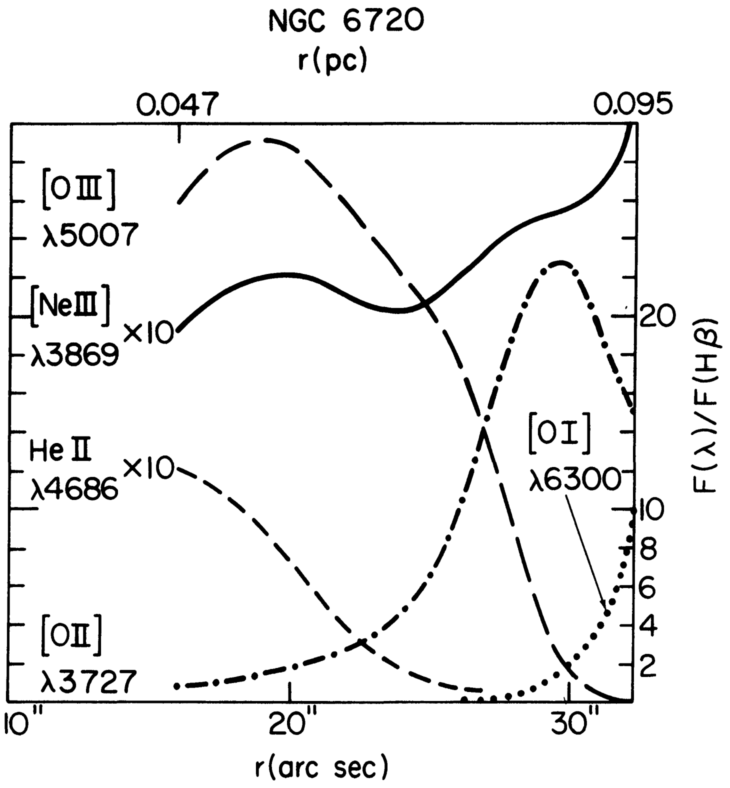

Figure 1. The strength of slected lines relative to Hβ as a function of distance from the central star.

and, what is more significant, this discrepancy was greatest near the central star but decreased to agreement with increasing radial distance.

Such behavior of course suggests fluorescent excitation of C$^+$ ions by starlight rather than recombination of C^{+2} ions. However, the upper level of the λ4267 transition is 4f $^2F^o$ and cannot be directly excited by absorption from the ground state, which is 2p $^2P^o$. Fluorescence would require a process such as the excitation of the nd ^2D levels, where n $\geq$ 5, followed by cascades to 4f $^2F^o$. Grandi (1976) made approximate calculations and concluded that recombination was an order of magnitude more important than fluorescence for λ4267 in the Orion Nebula. His calculations considered only "a few important levels", however, while one might expect that excitation of the higher n levels would dominate the fluorescent process (Seaton, 1968). This problem needs to be looked at with some care, especially since the λ4267 line is often used as the sole indicator of carbon abundance.

To show just how interesting the problem of C II λ4267 can be, consider the spectra of the hydrogen-poor knots near the nucleus of Abell 30 obtained by Jacoby and Ford (1983). In Knot 3, C II λ4267 is about half as strong as [Ne III] λ3967. If this line is interpreted as a recombination feature, it implies a C/O ratio of over 300! Now the [O III] λ5007/λ4363 ratio gives the temperature of Knot 3 as 16,000K. If, at this temperature, there really were 300 times more C^{+2} than O^{+2}, the C III] λ1909 radiation would be enormous. I don't see how photoionization heating could maintain such a temperature in the face of such cooling.

Could the intensity of λ4267 be due to fluorescence? The central star of Abell 30 is in fact much brighter than that of the Ring Nebula. But then why is Knot 4 without the λ4267 line? There are other strange things about these spectra. For example, the [Ne IV] λ4720 lines are far too strong compared with [Ne III] λ3869 for any reasonable Ne^{+3}/Ne^{+2} ratio or neon abundance. But it is important to try to understand such "monsters".

4. STELLAR WINDS AND NEBULAR SHELLS

To round out this collection of comments on physical processes in nebular shells, both understood and mysterious, I want to mention a common situation where interesting physical processes must be occuring, and where the question is whether we can observe the effects. This is the interaction between the nebular shell and the high velocity stellar winds ($v > 1000$ km sec^{-1}) observed in so many cases.

The stellar wind carries mass, momentum and energy. For specific values, consider the case of IC 3568 (Harrington, 1982). The wind velocity is 1840 km/sec and the mass loss rate appears to be at least 4.(-9) $M_{\odot}$/yr. Thus the kenetic energy carried by the wind is 1.4 $L_{\odot}$. With an expansion velocity of 7 km/sec, the age of the nebular shell is of the order of 2000 yrs. Clearly the present wind will add very little mass to the nebular shell over such a period of time.

If the wind were able to cool quickly after impact with the nebular shell, it would transfer its momentum to the shell, and this momentum might be large enough to have some influence on the dynamics of the nebular expansion. Compared with the stellar luminosity of 10^3 $L_{\odot}$, the radiation which would be generated by the cooling wind might seem small. IC 3568, however, is very thin in the Lyman continuum and the nebula captures only a small fraction of the stellar radiation. The Hβ luminosity is just L(Hβ) = 0.8 $L_{\odot}$. Thus if radiation produced by the wind had a characteristic spectral signature, it could be observed.

Alternatively, the wind, after being heated by encounter with the nebula, may not cool, but instead fill the cavity between the nebular shell and the star with a very hot, tenuous gas. The pressure of this "coronal" gas will be much more effective in accelerating the nebula than the simple transfer of wind momentum. This is the model presented by

Pikel'ner (1968, 1973). A similar picture of the effect of the winds from O-type main sequence stars on the interstellar medium has been worked out in some detail by Weaver et. al. (1977), where the hot, shocked stellar wind blows "interstellar bubbles". An important point is the high temperature of the shocked stellar wind: for an adiabatic shock we have $T = (3/16)(\mu/k)\ v_\infty^2$, which for $v_\infty = 1840$ km/sec yields $T = 5 \cdot 10^7$K. Since the mean free path of such hot particles is very large, the shock itself would be of the collisionless type. That is, the wind streaming into the ambient material will generate plasma waves which scatter and halt the wind, and the waves in turn heat the electrons to these very high temperatures. For our conditions, this could happen in as little as 10^8 cm. The resulting hot gas is supposed to fill the cavity at a density of $n_H \simeq 1\ \mathrm{cm}^{-3}$, roughly in pressure equilibrium with the nebular shell. At this temperature and density, the cooling time of the coronal component is much greater than the age of the nebula, so that the only question is whether cooling can be effective at the interface with the nebular gas. In the case studied by Weaver et. al. the coronal gas is seperated from the cool gas by a conduction front. They found that heat loss by conduction was small enough that the solution was quite similar to that obtained neglecting such losses altogether.

But there is a very important difference between the problem studied by Weaver et. al. and the situation in planetary nebulae: the distance from the collisionless shock to the swept up interstellar gas is about 20 pc, while in a planetary nebula, the temperature drop from $5 \cdot 10^7$K to 10^4 K must occur over only about 0.01 pc. This makes a classical conduction front impossible because the mean free path of the electrons will be larger than the front itself. This is the situation discussed by Balbus and McKee (1982) in their study of the evaporation of interstellar clouds in the coronal component of the ISM, except that the geometry is turned inside out. As in their analysis, we might expect the hot electrons to penetrate right into the cool nebular gas. The cooling of the coronal component could be so great that it would cease to exist as such. The Coulomb heating by these electrons could still result in a hot layer at the inner edge of the nebula which might be observable, but the effects on the dynamics would be very different than the scenario proposed by Pikel'ner. This is an area of nebular studies where important theoretical and observational work may yet be done.

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OSTERBROCK: The agreement of your calculation of the [Ne III] and [O III] distribution in the outer part of NGC 6720 with the measurements of Hawley and Miller is very striking. Am I correct in thinking that you used a physically calculated charge transfer rate in your model work?

HARRINGTON: Yes. The rates used are the same as those in our model of NGC 7662 (Harrington, Seaton, Adams and Lutz, 1982, Mon. Not. R. Astron. Soc., 199, 517) which are mostly due to Butler, Dalgarno and co-workers.

MATHIS: Would not the presence of even a small magnetic field stop the penetration of the "hot" electrons from the shocked wind into the nebular shell? The Larmor radius then determines the distance which the electrons can penetrate.

KAHN: Surely, you cannot have just the fast electrons going forward into the nebular shell because space charge neutrality must be maintained. There would very probably be plasma instabilities at the interface because of the anisotropy in the thermal velocity distribution there.

COHEN: In the light of your knowledge of IC 3568, would you expect dust grains to be present in this nebula? Mike Barlow and I found (at most) a weak 10 μm excess, but I recently detected IC 3568 weakly at 40 μm and strongly at 100 μm. I am wondering whether this radiation might come from cool grains.

HARRINGTON: IC 3568 is completely ionized, as far as we can tell, but I see no reason why these should not be cool grains in the ionized gas. They will be heated mainly by starlight rather than Ly α.

FORD: If you consider a high velocity PN in or near the plane of the Galaxy which sees an external wind of 100 - 150 km s^{-1}, do you expect any observable effects (as in low velocity supernova remnants)?

HARRINGTON: These velocities are, of course, much smaller than those I was considering. It all depends on the density of the wind - if it were high enough, there would be an observable effect.

ALLER: Does the importance of charge exchange depend critically on the details of the model (N(H), $F_\nu(*)$ etc.)? We found that in nebular models of relatively low density and high excitation there could occur large overlap zones of O^{++} and H^o. On the other hand, in compact, low excitation, dense models there was no such overlap. Hence, allowance for this phenomenon has to be on a case by case basis.

HARRINGTON: That is absolutely correct, and worth stressing once more. In NGC 6720, the charge exchange processes are very important. On the other hand, in an optically thin nebula of lower excitation, charge exchange makes only a 25 per cent difference, and in other nebulae even less. This why I see little hope of finding general ionization correction formulae which can be applied to all PN.