HIGH OXYGEN ABUNDANCE IN A BRIGHT FILAMENT OF THE CRAB NEBULA

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Detailed stationary photoionization models with homogeneous chemical composition were constructed for a bright filament of the Crab Nebula centered ~42" W-SW of the pulsar. So far this filament is the only one which has been observed in the ultraviolet (Davidson et al, 1982), in the visual (Miller, 1978; Davidson et al, 1982) and in the near-infrared (Dennefeld and Péquignot, 1982), so that numerous constraints and meaningful tests of the models exist. On the other hand the computer program used in the calculations includes recently introduced atomic physics processes (charge exchange reactions and "low-temperature" di-electronic recombinations) and was tested and calibrated by means of models of the high-excitation planetary nebula NGC 7027 whose line spectrum shares some characteristics with that of the Crab Nebula.

The two final models obtained fit all important features of the observed spectrum, in particular the critical ratio [OIII] 4363/5007, within observational uncertainties: these models differ in the assumed shape of the ionizing continuum and can be considered as the two most extreme assumptions yet compatible with currently available continuum measurements in the ultraviolet and X-ray range.

The main features of the gas density distribution are as follows: (1) In order to explain the strength of [NeV] 3426 (and CIV 1549 as well), the thermal gas pressure of the high-excitation zone must be several times less than in the bulk of the filament; therefore this high-excitation zone has a low density and comprises much of the volume of the filament. (2) In order to explain the strength of the "photon-counting" line HeII 4686, the high-excitation zone must substand a larger solid-angle, as seen from the source, than the low- or intermediate-excitation zones (emitting, e.g. [OI], [OII] and a fraction of [OIII]); this is in harmony with point (1) above if the filaments are cylinder-like.

The inferred elemental abundances are quite similar in both models and differ remarkably from previous determinations based on model calculations in that not only helium but the heavy elements C, N, O, Ne, S

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as well are markedly overabundant with respect to hydrogen so that, when the abundances are given in number per nucleon, they appear fairly typical of Population I.

This finding allows one to solve an old dilemma concerning the progenitor of the supernova. Until now the abundances (per nucleon) of the heavy elements, notably oxygen (the most easily accessible), were believed to be no more than one third the cosmic value (e.g. Davidson, 1979) so that the progenitor should have been a Population II and therefore very low mass star which would have expelled a large amount of helium with at most a moderate enrichment of heavy elements. This did not match any known scenario of supernova explosions and the Crab Nebula, the closest and best known supernova remnant, appeared as an extraordinary object that could not be attributed any reasonable status. In fact the situation was so uncomfortable that the recent proposals for the explosion involved a ~10 $M_{\odot}$ Population I star (e.g. Chevalier, 1977, Nomoto, 1983, Nomoto et al. 1982) and therefore simply ignored the underabundance of heavy elements in spite of repeated claims of Davidson and others.

Another important result of our calculations is that the abundance of nitrogen is certainly not more than normal with respect to oxygen so that there is no trace of the well-known enrichment which characterizes the CNO bi-cycle. This implies that the gas forming the filament has been somehow further processed at high temperatures favorable to helium burning. Since oxygen and carbon are roughly normal (the latter less accurate) while neon may be slightly overabundant (~ factor 2), this material should not have been processed beyond the very beginning of shell helium-burning and negligible mixing with inner C-rich layers should have occurred. The small amount of hydrogen presumably results from mixing with more external (unprocessed) layers of the star. The scenario recently proposed by Nomoto et al (1982) based on a ~ 9.5 $M_{\odot}$ progenitor accounts for the abundances of helium and oxygen but predicts an overabundance of nitrogen. A way to preserve the basic features of their attractive scenario may be to accept that, contrary to their expectation, the passage of the supernova shock wave burned a large fraction of nitrogen at least in some specific layers of the H-He envelope. Our result would then suggest that very little mixing occurred during or after the explosion.

A discussion of the photoionization models and of the reasons why previous analyses reached a different conclusion about abundances is given by Péquignot and Dennefeld (1982).

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DISCUSSION

WOLTJER: What is changed if you allow for some shock or other collisional heating in addition to photoionization energy input?

PEQUIGNOT: The answer to your question depends at once on the place where the complementary heating would be effective and on the problem that this heating would be supposed to solve:
1. An extra-heating of the highest excitation zone would mainly amplify CIV which, in the present schematic models, tends indeed to be small (although still within the observational uncertainties). Keeping in mind our procedure of convergence based on [NeV], a smaller contrast in thermal pressure between the high- and low-excitation zones would follow.
2. An extra-heating of the high- or intermediate-excitation zone would oblige the consideration of even higher elemental abundances since our final models were obtained by enforcing that the temperature-dependent line ratios (notably [OIII] and [OII]) be in agreement with observation. Also the collisionally excited lines would grow stronger relative to Hβ: since, with photoionization alone, they may tend to be slightly too large, we must conclude that the supplementary heating is moderate.
3. An extra-heating of the low-excitation zone would lead, in the framework of our rough models, to a smaller optical thickness of the filament without other significant consequences.

Now if the extra-heating is thought as an ad hoc alternative to explain the collisional high-excitation lines without considering, as we did, an ad hoc gradient of thermal pressure, then I believe that major difficulties would have to be faced. In effect [NeV] 3426 is perhaps the best indicator of pure photoionization by hard radiation since the collisional excitation of this line is perfectly effective at moderate temperature while any collisional ionization of Ne^{+3} to Ne^{+4} requires very high temperatures which would entail extremely large (and not observed) consequences on other lines such as CIV 1549. In a word the pressure gradient seems virtually unescapable provided that [NeV] has really been detected, although its exact value is still controversial.