DISCOVERY OF THE MOLECULAR HYDROGEN ION (H_2^+) IN THE PLANETARY NEBULAE

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ABSTRACT

Low-dispersion spectra of fifteen planetaries and hot subdwarfs were obtained with the SWP camera on IUE and continuous flux distributions corrected for interstellar extinction were derived. Several planetaries, particularly the young planetaries of high surface-brightness, show anomalous flux distributions. The most anomalous case is NGC 6210. We suggest that these anomalies may be explained as absorption by H_2^+ in the nebula. For the case of NGC 6210, we derive a column density, $N(H_2^+) = 8 \times 10^{16}$ cm^{-2}.

OBSERVATIONS

During the first year of observation with the IUE, we made a survey of planetary nebulae with the short-wavelength spectrograph, mainly for the purpose of investigating winds in the central stars, but in the process, we derived continuous flux distributions for these objects. The results of this survey are that planetaries have flux distributions like what you would expect from hot central stars (i.e., fluxes increasing steadily toward shorter wavelengths), but a couple of planetaries had odd flux distributions.

Figure 1 shows the flux distribution for a typical case, NGC 1535, and for the most anomalous case, NGC 6210. The fluxes in the figure are absolute fluxes corrected for interstellar reddening and normalized arbitrarily so that $F_\lambda(1950Å) = 1$. We use NGC 1535 as a standard of comparison with NGC 6210, because the two central stars appear to have almost identical properties. The visual spectra indicate that both are early O stars with higher-than-main sequence gravities (Refs. 1, 2). As you can see from Figure 1, the ultraviolet line spectra of the two stars are also strikingly similar: in both, N V 1240 is a very strong P Cygni feature, while C IV λ1550 is weaker and fully in emission; and in both, the subordinate line of OV λ1371 is also a strong P Cygni line. What is markedly different between the two spectra is their continuous flux distributions: the flux of NGC 1535 increases steadily toward shorter wavelengths, as you would expect for a hot star, but the flux of NGC 6210 drops off from its extrapolated values at wavelengths shorter than about 1500Å. Clearly, there is some source of absorption at the shorter wavelengths.

It is difficult to explain this difference as the effect of interstellar extinction, since several lines of evidence indicate that both NGC 1535 and NGC 6210 have similar, low amounts of reddening. The ratio of nebular radio flux density to Hβ flux yields a color excess, E(B-V) = 0.09 for NGC 1535 and E(B-V) = 0.06 for NGC 6210 (Ref. 3). The Ca II K line is weak in both visual spectra. In the case of NGC 6210, we obtained an LWR spectrum and found that the λ2200 extinction bump is consistent with a color excess, E(B-V) = 0.06.

INTERPRETATION

The two questions we have to ask, then, are (1) what is absorbing far-UV flux from the central star of NGC 6210, and (2) where does the absorbing material originate? The first question is relatively easy to answer because the flux deficiency looks just like the signature of the molecular hydrogen ion, H_2^+. This identification is supported by a quantitative comparison of the observations with the theoretical absorption properties of H_2^+. Figure 2 shows this comparison. The jagged line is the ratio of the relative fluxes of the two planetaries, while the smooth curve is the run of H_2^+ absorption, $e^{-\tau}$, for H_2^+ in the ground vibrational state, based on cross-sections calculated by Dunn (Ref. 4) and a column density of 8×10^{16} per cm^2.

The other question, where does the absorption come from, is also not difficult to answer because there are not too many places left to look. As I mentioned earlier, the spectra of the central stars of NGC 1535 and NGC 6210 are similar, and the amount of reddening of these two objects is also similar, so we can rule out the stellar atmosphere and the interstellar medium as the place in which the H_2^+ originates. There is just one place left to look, and that is the nebula itself.

Does this interpretation make sense? Should we expect H_2^+ in planetary nebulae? The answer, as Black (Ref. 5) has pointed out, is no, if you are considering a steady-state nebula. But NGC 6210 is a young nebula, still optically thick in H I (Ref. 6), so let us consider evolving nebulae, as illustrated in Figure 3. It is generally believed that planetary nebulae are the former envelopes of red giants. These envelopes were sloughed off due to the mechanical force of radiation pressure exerted on the gas and dust (Refs. 7, 8). Since the envelopes of red giants are basically composed of molecular hydrogen, and since the formation of the nebula is believed to be a cold flow, we can expect a planetary nebula to be initially composed of H_2. The loss of the red giant envelope, however, exposes the hot, inner stellar core, and radiation from the core, which is now seen as a central star, then proceeds to ionize the nebula. As the ionization front advances through the expanding nebula, it forms a thin shell of H_2^+:

$$H_2 + h\nu \rightarrow H_2^+ + e.$$

The H_2^+ generated by photo-ionization will be distributed among various vibrational states, but what we observe is absorption by H_2^+ from the ground vibrational state. We haven't done the necessary calculations, but it seems plausible that most of the H_2^+ generated by photo-ionization relaxes to the ground state as the result of collisions. Ground-state H_2^+ is destroyed by the inner edge of the H_2^+ shell by photo-dissociation:

$$H_2^+ + h\nu \rightarrow H^+ + H,$$

(It is this process that produces the absorption that we observe in NGC 6210) and by dissociative recombination,

$$H_2^+ + e \rightarrow H + H.$$

Supporting circumstantial evidence on H_2^+ shells in young planetary nebulae comes from the success rate of finding molecular hydrogen in planetary nebulae. In a survey of nine planetaries, Beckwith et al. (Ref. 9) found H_2 emission in five, four of which were young, high-density nebulae or their progenitors. All five nebulae with detectable H_2 showed [O I] as does NGC 6210.

We believe our detection of H_2^+ in NGC 6210 is significant not only because it represents a first detection of H_2^+ in planetary nebulae, but also because it should help to clarify our picture of nebular evolution.

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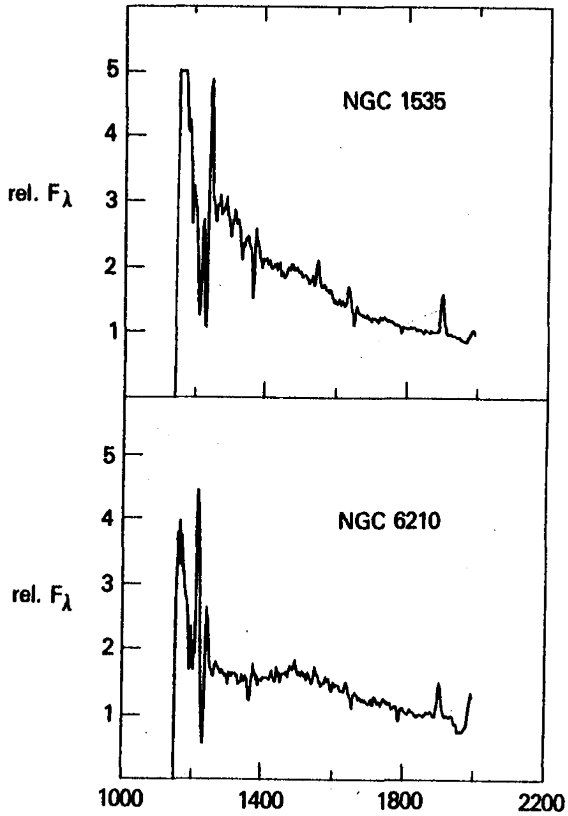

Figure 1. Relative Flux Distributions of NGC 1535 (SWP 3374) and NGC 6210 (SWP 3327). The raw fluxes contain ITF errors, but the effect of these errors should be small. The absolute fluxes were corrected for interstellar extinction on the assumption that E(B–V) = 0.06 for NGC 6210 and E(B–V) = 0.09 for NGC 1535.

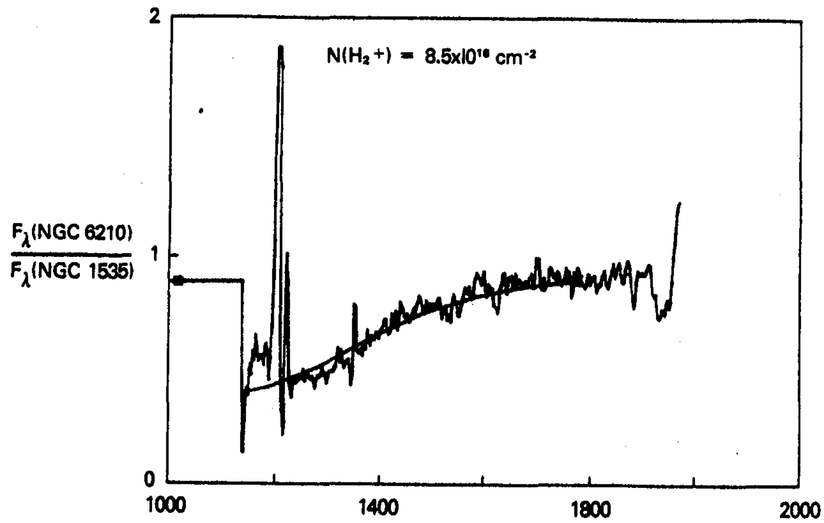

Figure 2. Comparison of the Observed Flux Ratio with Predicted Absorption by H_2^+. The jagged line is the ratio of the relative fluxes shown in Figure 1. The smooth curve is $\exp(-N\sigma_\lambda)$.

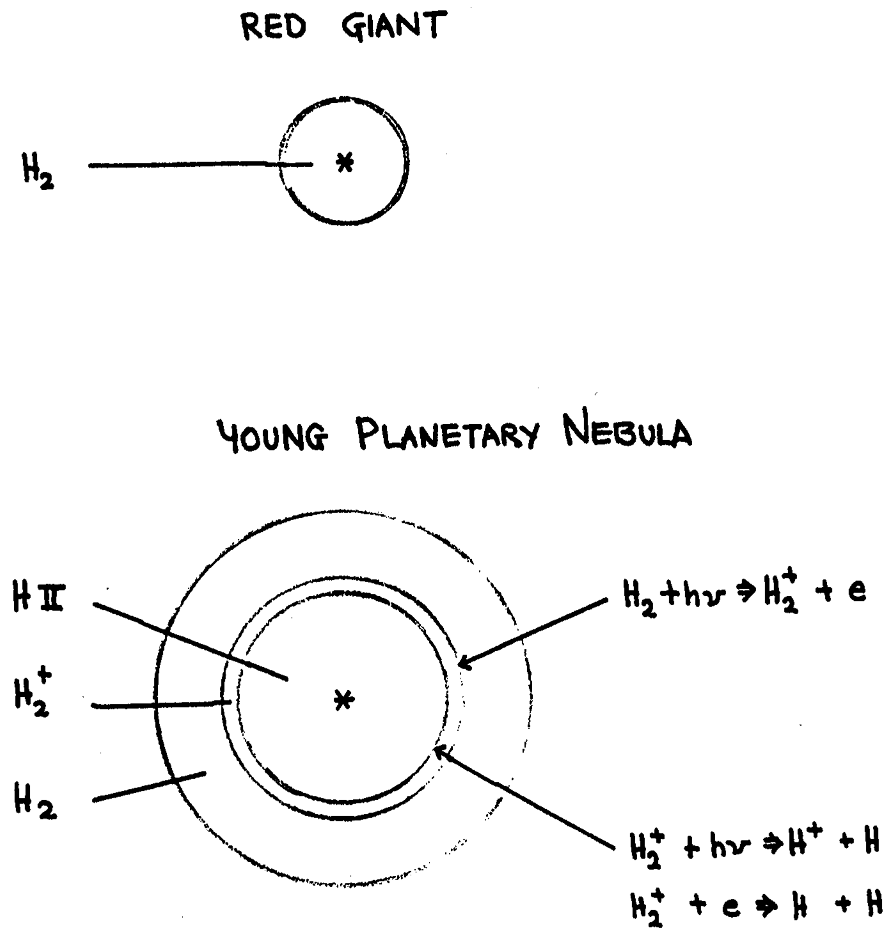

Figure 3. Evolutionary Scheme for Planetary Nebulae.