Carbon-Rich Photodissociation Regions: Star Formation Regions and Planetary Nebulae

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I. Photodissociation Regions

The ubiquity of interstellar regions in which the physics and chemistry are dominated by the effects of far ultra-violet (FUV) photons is now well understood (see, e.g., Hollenbach & Tielens 1997**, ARA&A, 35, 179**). Such regions, called photodissociation regions, or sometimes photon dominated regions (PDR), are observed to be present near sites of active star formation, the diffuse ISM, active galactic nuclei, and planetary nebulae – or anywhere the flux of FUV photons is large enough to influence the heating and chemistry of the region. Such regions emit nearly all of the far infrared emission in the Galaxy and comprise most of the mass. Detailed models of PDR, both low and high density regions, have been very successful in reproducing observations. All detailed models to date have been for an oxygen rich chemistry (C < O). The majority of the ISM is likely oxygen-rich, but it is not necessarily so everywhere (see Latter 1991**, ApJ, 337, 187**). We have begun a modeling program directed towards a detailed modeling of PDR that are carbon-rich (C > O). Such regions might be present and identifiable in the general ISM, but are also clearly present in the circumstellar envelopes around highly evolved stars and planetary nebulae. Our goals are to identify unique diagnostics of carbon-rich PDR, to reproduce observations already available of carbon-rich planetary nebulae, and to suggest further diagnostic observations of these regions. Implications for SIRTF and SOFIA observations will be directly addressed.

We present the first results from this study. The complete work will be presented elsewhere (Latter & Tielens, in preparation). An extensive parameter space exploration is being made, comparisons with oxygen rich environments, and new observations predicted – as well as offering a better base on which to interpret current observational data. Since planetary nebulae offer the clearest and most extreme cases of carbon rich environments currently known, our initial work concentrates on these objects. Here we discuss the model, display a sample of our results, and discuss planetary nebulae as PDR and the object NGC 7027 as an example of an extremely carbon rich PDR.

II. Photodissociation Regions in Planetary Nebulae

Evolution of stars from the asymptotic giant branch (AGB) to planetary nebula (PN) and beyond is one of the least understood phases of stellar evolution. Through a combination of stellar pulsations and radiation pressure on newly condensed dust, the star ejects an extended envelope. As the star ascends the AGB the mass loss rate increases to $dM/dt \approx 10^{-4}$ $M_\odot$ yr^{-1} ($v \approx 20$ km s^{-1}) near the tip of the AGB. Because of high densities and low temperature the envelope is predominantly molecular. As the star evolves off the AGB, a secondary wind – the "fast wind," which has much less mass but comparable momentum to the red giant wind – develops and begins to plow into the slower red giant wind. It has been thought that the interaction of the fast wind with AGB ejecta leads to the shaping of the resulting PN. In particular, the presence of a (small) initial asphericity will become amplified, and the variety of PN shapes (spherical, elliptical, butterfly, bipolar, etc.) and structural features (i.e. disks, jets, ansae) can be explained by variation of inclination angle, opening angle, and polar to equatorial density contrast. When the central star becomes hotter than $T_* \approx 30{,}000$ K, a photodissociation region moves through the gas that quickly turns the nebula atomic.

NGC 7027: This well-studied PN is in a very brief, but important period of evolution. It retains much of the remnant AGB molecular envelope. There is emission from many PDR tracers including HCO^+ and CO^+ (Latter et al. 1993, ApJ, 419, L97) and near-IR H_2 emission (e.g. Latter et al. 1999, ApJ, submitted). Its compact size has made it difficult to determine the detailed structure. Our NICMOS data reveal the H_2 emission to be biconical, or butterfly, shaped much like M 2-9 and Hubble 12 (Hora & Latter 1994, ApJ, 437, 281; 1996, ApJ, 461, 288). Results of detailed 3-D modeling suggest multiple structural components (Latter et al. 1999). That study presents an argument suggesting the morphological evolution of many PN is dominated by the effects of a PDR moving through an axisymmetric circumstellar envelope – not the most often invoked interacting winds model.

TABLE 1: Selected Model Results

Inputs:	Model 1	Model 2	Model 3	Model 4
n_{tot} (cm^{-3})	1.0(+6)	1.0(+6)	5.0(+4)	5.0(+4)
G_0	1.0(+5)	1.0(+5)	1.0(+5)	1.0(+5)
ζ_{CR} (cm^3 s^{-1})	1.8(-17)	1.8(-17)	1.0(-40)	1.0(-40)
C/H	1.5(-3)	3.0(-4)	1.5(-3)	3.0(-4)
O/H	3.0(-4)	6.0(-4)	3.0(-4)	6.0(-4)

N/H	1.0(-4)	1.0(-4)	1.0(-4)	1.0(-4)
L_* (L_{sun})	6000	6000	6000	6000
T_* (K)	200,000	200,000	200,000	200,000
Calculated Peak Abundances ($A_V < 10$ mag):				
H_2	5.0(-1)	5.0(-1)	5.0(-1)	5.0(-1)
C	1.2(-3)	2.2(-4)	1.2(-3)	2.7(-4)
CO	3.0(-4)	3.0(-4)	3.0(-4)	3.0(-4)
CO^+	3.5(-10)	2.2(-10)	3.1(-11)	3.2(-12)
HCO^+	8.9(-10)	4.5(-9)	1.6(-11)	3.4(-11)
C_2	5.3(-4)	3.4(-8)	5.6(-4)	2.2(-9)
CN	1.5(-6)	2.5(-7)	1.3(-6)	1.1(-8)
C_2H	3.5(-5)	3.5(-9)	1.7(-5)	1.7(-10)
C_2H_2	7.0(-9)	4.5(-13)	1.5(-11)	3.4(-14)
Calculated Column Densities (cm^{-2}):				
N(C)	1.2(+19)	2.3(+17)	1.4(+19)	3.8(+17)
N(CO^+)	5.2(+11)	3.1(+11)	2.9(+10)	3.2(+9)
N(HCO^+)	7.2(+11)	1.3(+13)	3.0(+10)	9.3(+10)

[1] 1.0(+6) = 1.0×10^6

III. The Chemical Model

The chemical model developed for this work is based on the extensive PDR code originally developed by Tielens & Hollenbach (1985, ApJ, 291, 722). It produces one-dimensional, uniform density models that extend from the far-ultraviolet illuminated ionized edge of a cloud to A_V = 10 magnitudes into the neutral gas. A full assessment of the heating and cooling is made, including photoelectron ejection from grains. For a number of important observable species, excitation and line strengths are determined. We have extensively modified the chemical network from which steady state atomic and molecular abundances are determined as a function of depth into the cloud. The new chemical network includes:

- 94 atomic and molecular species.
- 1270 reactions.
- reaction rates generally taken from the UMIST database. Some have been adjusted for this application.
- a limited PAH, PAH^-, and PAH^+ chemistry.
- a determination of chemical abundances in carbon-rich and oxygen-rich PDR environments.
- effects of X-ray illumination on the cloud through X-ray ionization and heating (Natta & Hollenbach 1998, A&A, 337, 517). The strongest influence by X-rays is at the illuminated surface of the cloud.
- the effects of excluding cosmic ray ionization and dissociation, because cosmic rays might be prevented from penetrating planetary nebulae.

A full listing of the chemical network will be made elsewhere (Latter & Tielens, in preparation). Table 1 displays some selected results. Here we show both carbon and oxygen rich models for comparison. These models include the X-ray flux from a nearby hot star like a planetary nebula nucleus.

IV. Conclusion

While these are only early results, it is evident that carbon rich PDR have unique and easily identifiable characteristics. For planetary nebulae, these models are helping to understand the evolution, overall morphology, and composition of extremely carbon rich objects, such as NGC 7027. The exclusion of cosmic rays from the planetary nebula PDR causes strong and observable differences in the overall chemistry of the nebula. Such models will help to constrain the degree to which cosmic rays penetrate planetary nebulae. This work will continue with addition of 2-dimensional and nonuniform density distributions, and will include time dependent variation of the FUV source and density structure.