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Lyα Photolysis in the Primitive Solar Nebula

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1 Introduction and Overview

This is the final report for the third year of work on this project. For the first two years of the project, the grant number was (NASA NAGW-4357, SwRI project number 15-7130).

Our proposal was to quantitatively investigate the importance of photochemistry in the solar nebula. In the generally accepted theory for the chemical evolution of the primitive solar nebula, *Prinn and Fegley* [1989] argued that photochemistry is unimportant, and that thermochemistry controls the relative abundances of molecular species throughout the planet-forming region. They provided useful estimates of the chemical energy available to the solar nebula from a variety of sources, and established that even the small photolysis rate due to starlight is more important than the photolysis rate from direct sunlight (although small, the UV flux from starlight could have processed a non-negligible fraction of the solar nebula [e.g., *Wood and Chang* 1985]). The reason for this is that the opacity of the disk was so large that direct sunlight could only penetrate to 0.1 AU or so, despite the expectation that the protosun, if comparable to a T–Tauri star, would be emitting up to 10^4 more H I Lyα photons than the current sun [*Zahnle and Walker* 1982].

However, *Gladstone* [1993] pointed out that for H I Lyα (and for other strong solar ultraviolet resonance lines, such as He I 584 Å), *Prinn and Fegley* [1989] neglected the contribution due to backscattering by atoms in the interplanetary medium (IPM) and nearby interstellar medium (ISM).

The current brightness of interplanetary H I Lyα in the vicinity of the Earth is about 400 Rayleighs (i.e., about 4×10^8 photons cm^{-2} s^{-1} over the entire sky) [*Ajello et al.* 1987]. For comparison, the direct H I Lyα flux from the sun is currently about 3-5 $\times 10^{11}$ photons cm^{-2} s^{-1} at the Earth [*Mount and Rottman*, 1985]. Although the direct flux is a much more important source in the inner solar system, the interplanetary source falls off much more slowly than the direct flux [*Ajello et al.* 1987], so that the two sources are of comparable strength at the orbit of Neptune [*Broadfoot et al.* 1989].

We developed a Monte Carlo resonance line radiative transfer code, capable of accurately calculating the radiation field of H I Lyα, He I 584 Å, and He II 304 Å emissions throughout the nebula and the nearby interstellar medium in which it is embedded. We applied the code to two appropriate models of the primitive solar nebula. Our model provided the photolysis rates of various species over the entire surface layer of the nebula, and from this we evaluated the importance of UV photochemistry due to backscattered solar UV resonance line emissions on different parts of the nebula. The results discussed below were presented at a special "Origins" session during the fall meeting of the American Geophysical Union which was convened by Drs. Janet Luhmann and Jeff Cuzzi.

2 Results

These are the main results of our work. As shown in Fig. 1, there are several possible interstellar medium (ISM) regimes in which the solar system could be embedded. Currently, we are in a thin part of the ISM, but it is likely that over the 4.6 By age of the solar system that we have spent significant amounts of time in each regime, beginning with formation in a cloud. Using the Monte Carlo code we developed for simulating solar resonance line transport in the interstellar medium, we performed runs for the current ISM conditions, which are shown for the bright H I Lyα and He I 58.4 nm lines in Fig. 2.

The general behavior of the scattered resonance line radiation is found to be well-approximated by combining simple expressions for the optically thin and optically thick limits, as follows.

The direct solar flux at a given distance r from the Sun is given by

$$J_{\rm direct} \; = \; \frac{F_\odot}{r^2} \, e^{-\tau_{disk}(r)} \sim \; 0 \qquad \text{(since } \tau_{disk} >> 1\text{)} \tag{1}$$

The backscattered interplanetary medium brightness may be approximated under optically thick and optically thin conditions as

$$J_{\rm IPM} \; \approx \; \frac{1}{2}\frac{F_\odot}{r^2} \qquad \text{(optically thick)}$$

$$J_{\rm IPM} \; \approx \; \frac{1}{2}\frac{F_\odot}{r} \; k_{\rm sca}(r) \, \frac{\Delta\lambda_{\rm IPM}}{\Delta\lambda_\odot} \qquad \text{(optically thin)} \tag{2}$$

where $\Delta\lambda_{\rm IPM}$ and $\Delta\lambda_\odot$ are the line-widths of the appropriate resonance line in the interplanetary medium and emitted by the Sun, respectively, and $k_{\rm sca}(r)$ is the line-center extinction due to scattering. By simply combining these two limits, we obtain an expression useful for approximating the backscattered mean intensity in both optically thick and optically thin regimes:

$$J_{\rm IPM} \; \approx \; \frac{1}{2}\frac{F_\odot}{r^2} \left[\frac{r \; k_{sca}(r) \; \frac{\Delta\lambda_{\rm IPM}}{\Delta\lambda_\odot}}{1 \; + \; r \; k_{\rm sca}(r) \; \frac{\Delta\lambda_{\rm IPM}}{\Delta\lambda_\odot}} \right] \tag{3}$$

The results using Eq. 3 are shown by the dashed lines in Fig. 2, and are shown for each of the four ISM regimes in Fig. 3. It may be seen that as the ISM density increases, the turnover from optically thin $(1/r)$ to optically thick $(1/r^2)$ regimes occurs at smaller r. This figure indicates that, even with a very thick and opaque disk between the Earth and the Sun, that the IPM H I Lyα and He I 58.4 nm fluxes throughout the solar system would be comparable to the direct fluxes today, for the case of a dense or cloud ISM environment.

Combining the mean intensities estimated for the dense ISM with the densities calculated for two different model solar nebulas (chemical equilibrium and kinetically-inhibited), we estimate column photolysis rates for several important species in Fig. 4. Because they are abundant species and may be photodissociated by H I Lyα radiation, both H_2O and CH_4 may be strongly affected by backscattered IPM radiation (especially in the important 1–5 AU region).

Finally, we compare the photolysis lifetimes due to backscattered-IPM emissions with the solar nebula lifetime in Fig. 5. It is clear that the more volatile, strongly-bonded species such as CO and N_2 are unaffected by the IPM, but the condensible species such as H_2O,

NH_3, H_2S, and CH_4 may be affected in the 1–5 AU region on timescales comparable to the lifetime of the solar nebula. Note that we have assumed in all these calculations the current solar fluxes at H I Lyα and He I 58.4 nm. The brightnesses and photolysis rates in Figs. 2, 3, and 4 will scale proportionally to these fluxes, and the lifetimes in Fig. 5 will vary inversely, so that for a T-Tauri-stage Sun, the effects will be more important.

3 References

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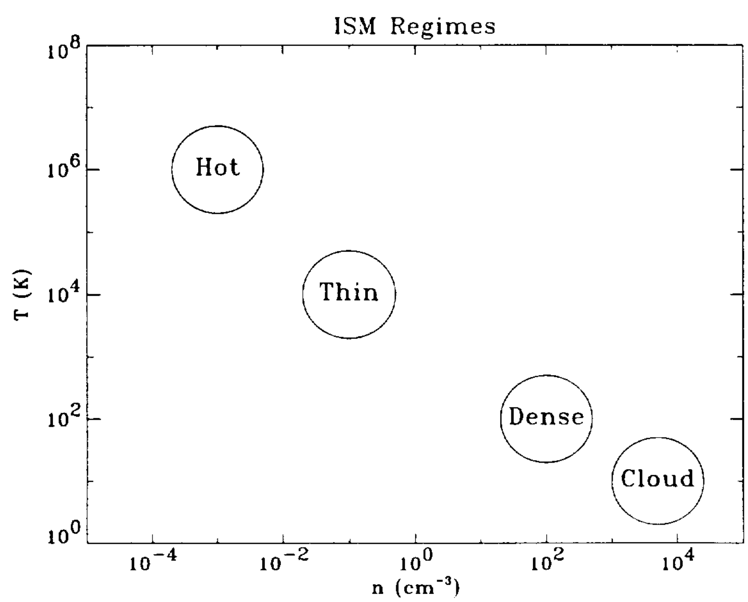
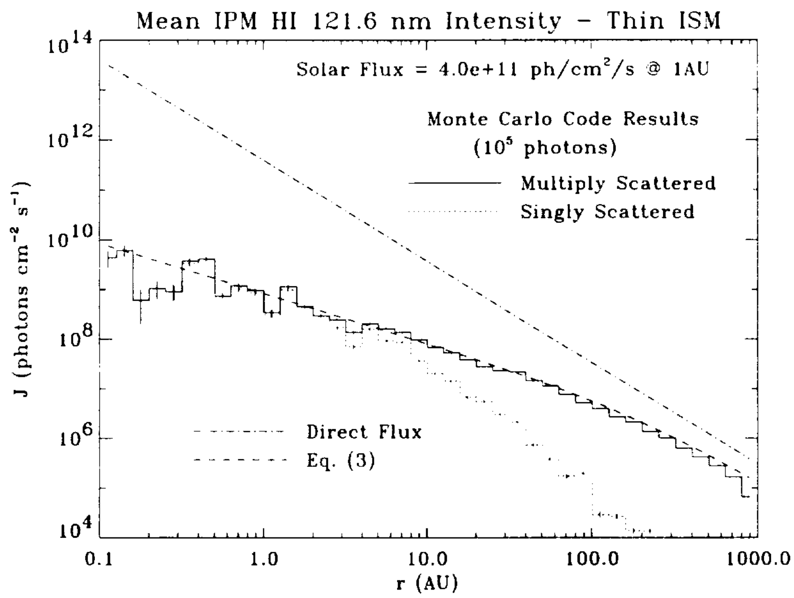


Fig. 1—The different interstellar medium (ISM) regimes. The solar system is currently in a "thin" regime, but is likely to have spent substantial time in each of the other regimes as well, after having formed in a "cloud" regime.



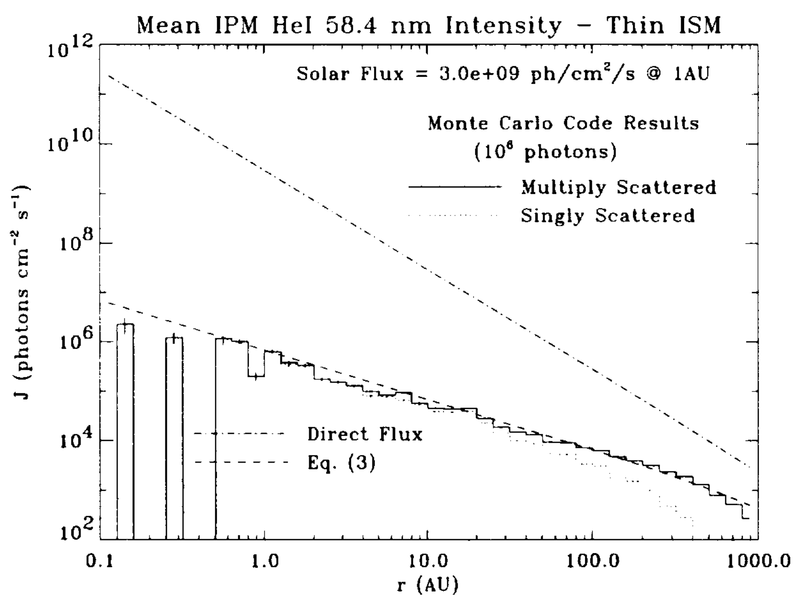


Fig. 2—Monte Carlo interplanetary medium (IPM) scattering results (solid line, multiple scattering; dotted line, single scattering) compared with a simplified expression (Eq. 3, dashed line) for (upper panel) H I 121.6 nm (Lyα), and (lower panel) He I 58.4 nm. The dot-dash line indicates the direct solar flux in the absence of disk opacity.

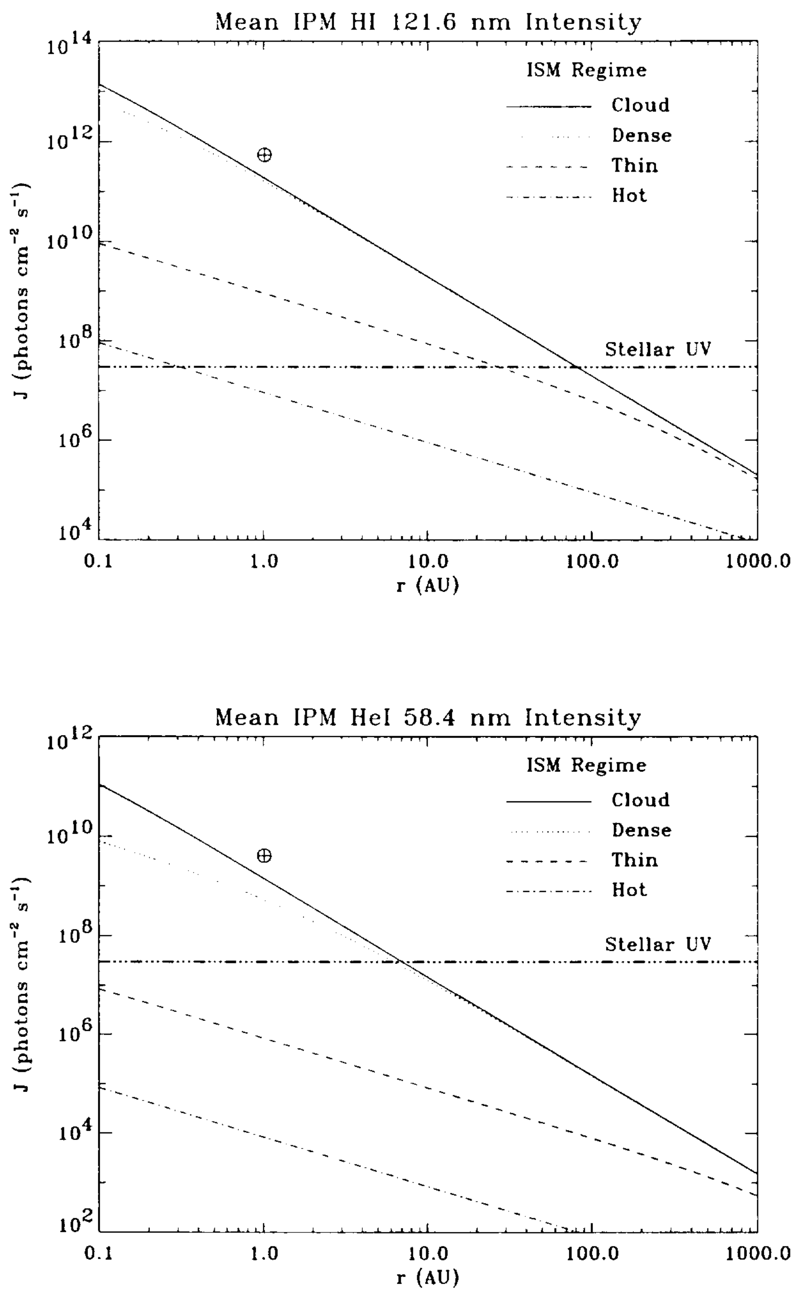


Fig. 3—The variation of IPM-backscattered brightness as a function of distance from the Sun expected for the four ISM regimes of Fig. 1, for (upper panel) H I 121.6 nm (Lyα), and (lower panel) He I 58.4 nm. The triple-dot-dash line shows the current stellar UV brightness for The Earth symbol indicates the the current direct flux from the Sun at the given emission.

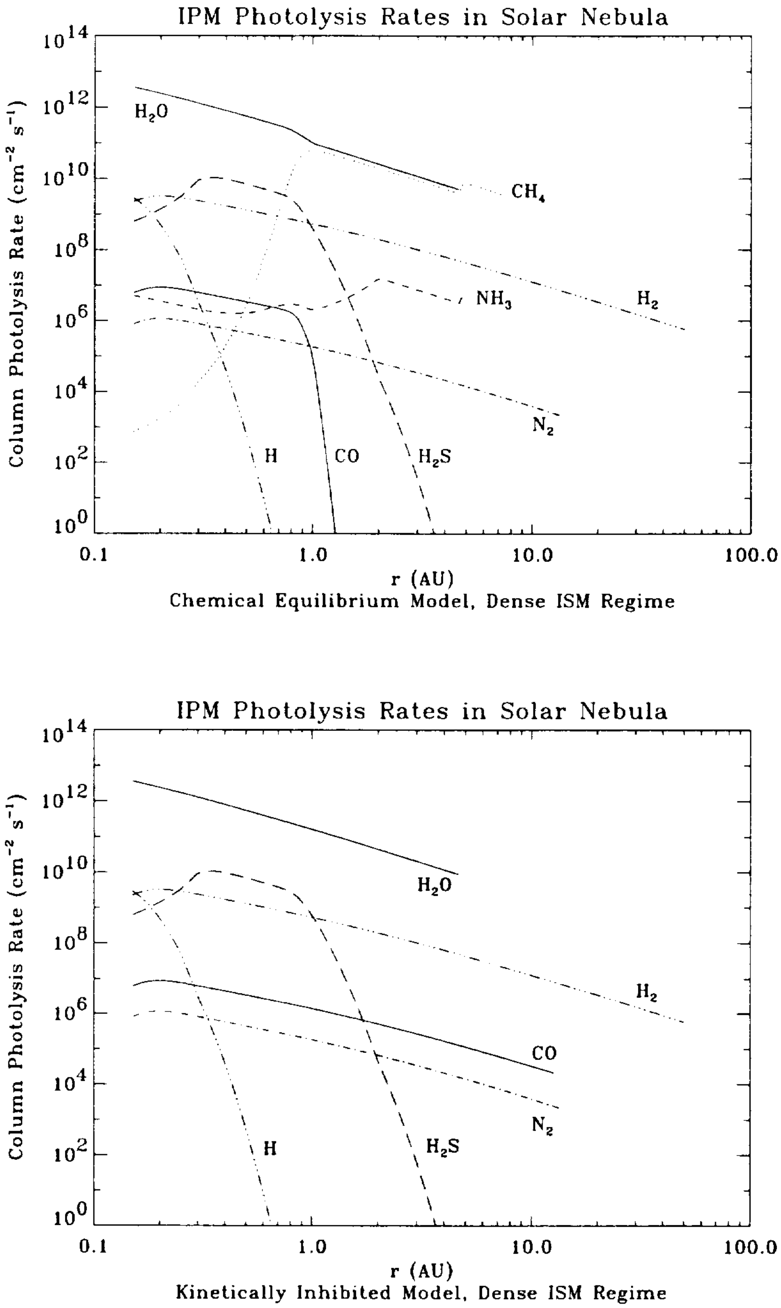


Fig. 4—Model photolysis rates resulting from IPM-backscattered H I 121.6 nm and He I 58.4 nm emissions, for a solar nebula in (upper panel) thermochemical equilibrium and (lower panel) one which accounts for the long time constants required for several of the reactions to reach thermochemical equilibrium (the kinetically-inhibited model). Only the photolysis rates for gaseous species are indicated.

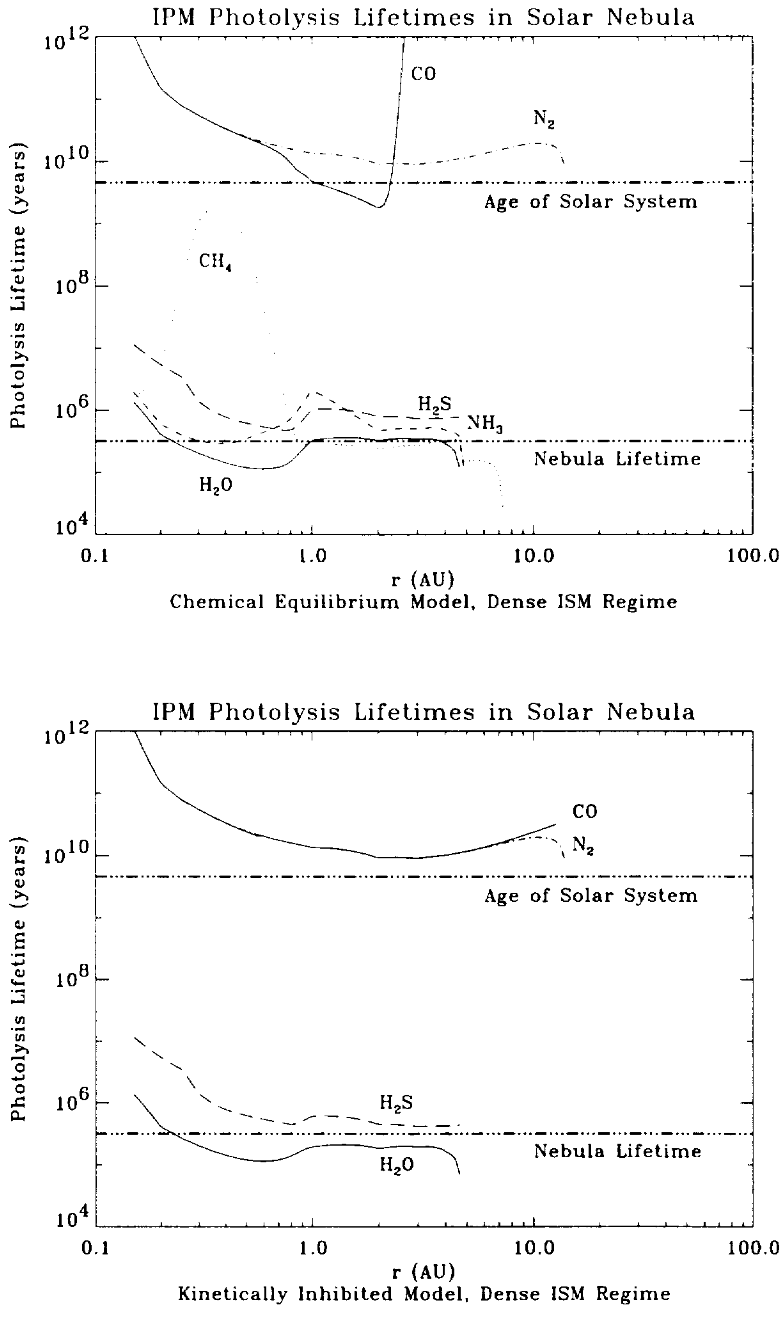


Fig. 5—Lifetimes for photolysis by IPM-backscatter of solar H I 121.6 nm and He I 58.4 nm in the solar nebula for various gases, in a (upper panel) thermochemical equilibrium and (lower panel) kinetically-inhibited model nebula. The triple-dot-dash lines show the expected nebular lifetime and the age of the solar system for comparison.