CO in the Atmospheres of Pluto and Triton

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The past 15 years have seen a remarkable increase in our knowledge of the Pluto-Charon system, though it has not yet been visited by a spacecraft. The discovery of Charon (Christy & Harrington 1978) and the observation of the mutual occultation event series in 1985–1990 (Tholen & Buie 1990) has enabled astronomers to deduce an impressive amount of information about Charon's orbit around Pluto, the sizes and albedos of the two bodies, and the mass of the system. Spectroscopic observations during this period also enabled the separation of their individual spectra in both the visible and near-IR (*e.g.* Fink & DiSanti 1988, Marcialis *et al.* 1987), while photometry both before and during the eclipse series has given information on their individual colours and albedos (*e.g.* Jones *et al.* 1988; Stern 1992). One of the most interesting results from these studies is that Pluto and Charon appear to have quite different colours and albedos, and by inference, different surface compositions. This has been confirmed by spectroscopy: in the near-IR Cruikshank *et al.* (1976) was the first to identify a plutonian surface constituent, CH_4 ice, without any evidence of water or ammonia, while Marcialis *et al.* (1987) found Charon's IR spectrum shows clear evidence of water ice but no evidence of several other ices, most notably methane.

Similarly, the June 1988 occultation by Pluto of a star (Elliot *et al.* 1989) allowed the discovery of a thin but distended atmosphere around Pluto. Yelle & Lunine (1989) and Hubbard *et al.* (1990) explored a range of parameters in modelling the thermodynamic balance of Pluto's atmosphere, and found that the temperature at height could be quite warm, rising to 106 K at altitudes above 10 km and remaining isothermal above this level. Moreover, Yelle & Lunine derived a mean atmospheric molecular weight $\bar{\mu} = 25 \pm 3$, which requires a heavier component to the atmosphere than CH_4 that dominates the composition. This picture was supported when Owen *et al.* (1993) discovered evidence for both N_2 and CO ice on Pluto's surface from near-IR spectra. From equilibrium vapour-pressure arguments at the low temperature of Pluto's surface, it seems likely that the atmosphere is composed mostly of nitrogen, with CO and CH_4 being minor and trace constituents, respectively. (The occultation data imply a surface number density $\sim 10^{14}$ cm^{-3}.) In these models the strong temperature gradient close to the surface and the warm upper atmosphere explain the occultation lightcurve (Elliot *et al.* 1989) and also fit more recent evidence of a cold surface, 30–44 K, from radio and FIR continuum measurements (Stern *et al.* 1993). In many respects, then, Pluto resembles Neptune's moon Triton, as revealed by the Voyager 2 encounter.

However, the actual composition of the atmosphere is unknown: the description above has been inferred from only the atmosphere's bulk properties, and these are derived only from the occultation lightcurve. Of the three gases N_2, CO, and CH_4, only CO is easily detectable in principle from Earth's surface. Thus at whatever concentration, it is important to try and detect CO from the atmosphere, at the very least to confirm its existence and extent. One might also ask, is there evidence in the CO emission of the atmosphere undergoing dynamical escape as postulated by Clarke *et al.* (1992)? If so, Pluto's atmosphere would be unique among the planets in this regard, and important knowledge of cooling and heating processes in such an atmosphere could be gained. Such knowledge may also have relevance to models of cometary outgassing.

Ordinarily, however, it would be virtually impossible to detect any such CO from ground-based telescopes simply because of Pluto's small size and great distance. For a typical single-dish telescope with a 1′ HPBW, beam dilution at 115 GHz would reduce an optically thick, thermalised 100 K atmospheric component to a signal strength of $T_R \sim 1$ mK (Barnes 1993), practically undetectable with modern mm-wavelength technology. Even with an interferometric beamwidth of 5″, the expected brightness would only be $T_b \sim 0.16$ K at 3 mm, still well beyond the reach of existing interferometers. However, Pluto's low surface gravity and volatile composition combine to produce what may be the only case in the solar system where hydrodynamic escape of the

atmosphere is occurring today. Models of this process (*e.g.* Clarke *et al.* 1992, who assumed a methane-dominated atmosphere, but whose results should be generally applicable) suggest that at $1.5R_P$ the number density is $\sim 3\times10^9$ cm^{-3} and at $4R_P$ it is still $\sim 2\times10^6$ cm^{-3} (*cf.* their Table I). At these densities any CO will still be thermalised to the ambient temperature (~100 K). In fact, except for the small source size, the excitation conditions in any extended CO-containing atmosphere would closely resemble those in a dense molecular core. For a column as long as the impact parameter at a projected radius of, say, $4R_P$, the column density will be 10^{15} cm^{-2} and, allowing for the higher densities closer to Pluto, much greater at smaller radii. *Thus an optically thick CO atmosphere around Pluto could be significantly larger than the solid body of the planet*, and the beam dilution in this case would be correspondingly less, possibly rendering the CO detectable with existing telescopes.

In the Figure and Table, I give the results of calculations which predict the brightness of any CO emission from Pluto's atmosphere. Similar numbers would apply also to Triton. Here I have used the model of Clarke *et al.* (1992) which gives the scale heights and temperatures in the atmosphere from the surface up. The line fluxes are determined by first calculating the atmospheric level above which the optical depth in the CO line is ~1. The Figure shows the continuum emission from both Pluto and Charon (the total values have been measured at various frequencies — see Stern *et al.* [1993] — but the two bodies' fluxes are not known separately), and a sequence of CO emission lines. There are three predicted flux levels, indicated by the dotted, dashed, and solid lines, for CO comprising 100%, 10%, and 1% of the atmosphere. Also shown are upper limits I obtained for the J=1→0 and 2→1 lines from Haystack and NRAO 12m observations.

TABLE — Predicted CO Line Flux Densities for Pluto

Line	R(1%) (km)	S(1%) (Jy)	R(10%) (km)	S(10%) (Jy)	R(100%) (km)	S(100%) (Jy)
1→0	1613	0.017	1748	0.020	2162	0.031
2→1	1690	0.073	1960	0.098	2915	0.22
3→2	1729	0.17	2099	0.25	3324	0.62
4→3	1753	0.30	2178	0.46	3557	1.2
5→4	1765	0.46	2276	0.76	3681	2.0
6→5	1770	0.65	2328	1.12	3727	2.9
7→6	1768	0.86	2310	1.5	3710	3.8
8→7	1761	1.08	2230	1.7	3638	4.6
9→8	1749	1.3	2165	2.0	3517	5.3
10→9	1732	1.5	2107	2.3	3350	5.8

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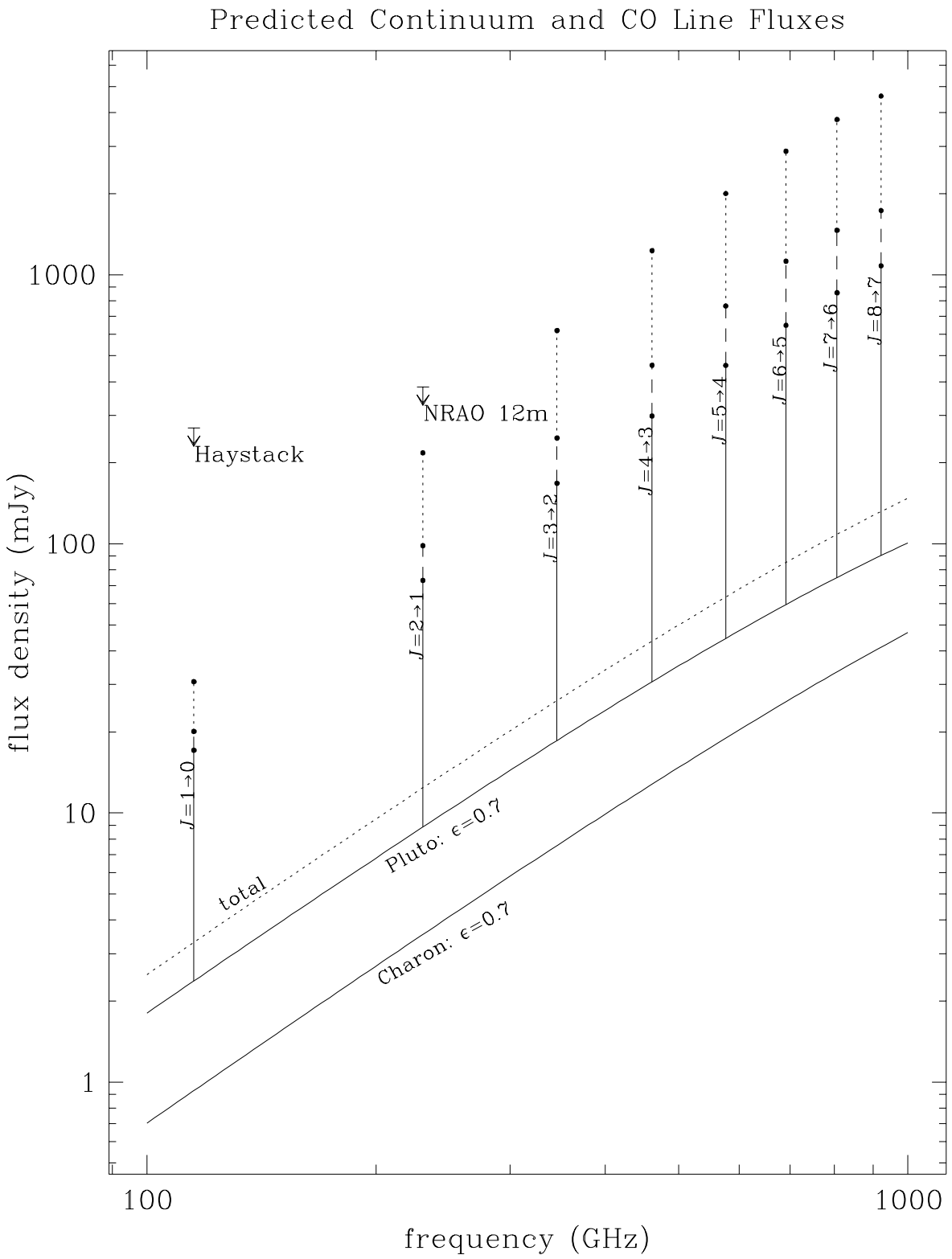
Predicted Continuum and CO Line Fluxes
flux density (mJy)
1000
100
10
1
100
1000
frequency (GHz)
Haystack
NRAO 12m
J=1→0
J=2→1
J=3→2
J=4→3
J=5→4
J=6→5
J=7→6
J=8→7
total
Pluto: ϵ=0.7
Charon: ϵ=0.7