Discovery of carbon monoxide in the upper atmosphere of Pluto

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ABSTRACT

Pluto’s icy surface has changed colour and its atmosphere has swelled since its last closest approach to the Sun in 1989. The thin atmosphere is produced by evaporating ices, and so can also change rapidly, and in particular carbon monoxide should be present as an active thermostat. Here we report the discovery of gaseous CO via the 1.3mm wavelength J=2-1 rotational transition, and find that the line-centre signal is more than twice as bright as a tentative result obtained by Bockée-Morvan et al. in 2000. Greater surface-ice evaporation over the last decade could explain this, or increased pressure could have caused the atmosphere to expand. The gas must be cold, with a narrow line-width consistent with temperatures around 50 K, as predicted for the very high atmosphere, and the line brightness implies that CO molecules extend up to ≈3 Pluto radii above the surface. The upper atmosphere must have changed markedly over only a decade since the prior search, and more alterations could occur by the arrival of the New Horizons mission in 2015.

Key words: Kuiper belt objects: Pluto – planets and satellites: atmospheres – submillimetre: planetary systems

1 INTRODUCTION

Pluto was the first body to be discovered in the Kuiper Belt of icy planetesimals orbiting in the outer Solar System. Although now only the second-largest body known in the belt (after Eris), Pluto is intensively studied, and is the primary target of the New Horizons mission (Stern & Spencer 2003), with a spacecraft flyby scheduled in 2015. In particular, Pluto offers the rare opportunity to study a very cold planetary atmosphere which also evolves strongly with time, and may in fact be transient, settling and freezing out on the surface (Owen et al. 1993) as Pluto recedes from the Sun in its highly elliptical orbit. As Pluto’s last perihelion was in 1989, subsequent contraction of the atmosphere was expected, but in fact when observed by occultation of stars the atmospheric pressure and size had increased between 1988 and 2002 (Elliot et al. 2003ᵃ). Around the same time, the surface ice had become redder, and also brighter around the northern pole as it came more into sunlight (Buie et al. 2010ᵃ,b). Many of these results were surprising, such as changes in albedo over as little as a year, and darkening of the southern regions, contrary to expectations if ices have been sublimating from here most recently.

The atmosphere and surface must be strongly coupled, since sublimation of ices supplies the atmosphere (Schaller et al. 2007, e.g.), and so as the composition of the surface changes seasonally (Buie et al. 2010ᵃ,b), the gas abundances should also evolve. Atmospheric temperatures of around 100 K (Elliot et al. 2003ᵇ) are much warmer than the surface at only 40 K (Tryka et al. 1994). This requires a complex thermal balance controlled by the relative abundances of molecules that absorb radiation and re-emit in cooling lines, plus there is an overall influence of the level of sunlight, particularly in the ultra-violet (Strobel 2008). The atmosphere is also very fragile, with a solar-driven slow wind predicted to be removing it into space (Delamere 2009, e.g.).

Such a cold diffuse atmosphere is difficult to study by remote observation, and most conclusions are presently model-based. The trace gas methane is the only one to have been confirmed spectroscopically (Young et al. 1997), Surface-ice spectroscopy shows frozen nitrogen dominates (Owen et al. 1993), with methane and carbon monoxide also present, plus possibly ethane (DeMeo et al. 2010) and nitriles (Protopapa et al. 2008). N₂ must dominate the atmo-
sphere as it vaporizes readily and is by a factor of 50 the most abundant ice (Owen et al. 1993), but sublimated CO is the strongest coolant (Strobel 2008) and so should act as the thermostat. Some evidence for CO includes the brightest patch on Pluto’s surface, suggested to be CO ice (Buie et al. 2010b, and references therein), and an extinction layer seen in atmospheric occultation, interpreted as droplets of N₂ or CO (Rannou & Durry 2009).

1.1 Previous searches for CO

Prior searches for gaseous CO have been made with ground-based telescopes. Infrared absorption spectroscopy has recently constrained CO:N₂ to be <0.5 % near the surface (Lellouch et al. 2010), an order of magnitude below an earlier limit (Young et al. 2001). There is also a long history of millimetre-wavelength searches, looking for rotational transitions of CO from the higher atmosphere (Barnes 1993; Bockée-Morvan et al. 2001). As the atmosphere is warmer than the surface, and extends beyond the planetary disc, emission lines are predicted. The major difficulty is that Pluto is small and distant, subtending less than a percent of the beam solid angle, even for telescopes of 10-30m class. An upper limit was first obtained using the Haystack 37m in 1993, for the CO J=1-0 transition rotational line at 2.6 mm wavelength (Barnes 1993). This limit was improved by the equivalent of eight-fold in 2000, with the IRAM 30m telescope (Bockée-Morvan et al. 2001), and this group also searched for the J=2-1 transition at 1.3 mm with better sensitivity. A tentative positive signal was seen, with the brightest spectral channel observed at 28 mK in main-beam brightness temperature, versus 1σ noise of 10 mK per 0.1 km/s spectral channel. However, the observation was severely affected by a strong line from a background Galactic cloud, coming as close as 0.5 km/s to potential Pluto emission (Bockée-Morvan et al. 2001).

The 2000 data suffered from an unfortunate coincidence in sky position with an uncatalogued Galactic source, but Pluto’s orbit as seen from the Earth has brought it closer to the Galactic Plane over the last couple of years. Here we present results from the 15m James Clerk Maxwell Telescope, making a new search for the J=2-1 line, at epochs chosen to minimise Galactic contamination behind Pluto. The search was motivated by time availability at an excellent millimetre-site, and the opportunity to examine the evolution of Pluto’s atmosphere in the exciting run-up period to the arrival of New Horizons (Stern & Spencer 2003). We report the confirmation of atmospheric CO (after two decades of searches), making it only the second gas-phase species to be detected, after methane (Young et al. 1997).
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Figure 2. Left: expanded version of Figure 1. Overplotted in red is the spectrum obtained in April 2000 by Bockêlee-Morvan et al. (2001) using the IRAM 30m, but re-scaled for equivalent signal with the 15m JCMT; the brightest channel near zero velocity is then $7 \pm 2.5$ mK over 0.1 km/s. Right: comparison of the average spectrum and the 2010 and 2009 data (top to bottom, offset for clarity).

Figure 3. Example spectrum if all 11 nights of data are weighted and co-added but no baselines are removed. The red channels were used to fit an example linear baseline, and this would extrapolate across the Pluto velocities as shown by the red straight line.

3 RESULTS

Figure 1 shows the co-added Pluto spectrum from 2009/10, in the dwarf planet’s rest-frame. A clear line is seen at zero velocity, with $6.5\sigma$ confidence in the integrated antenna temperature. There are no other significant narrow features; the next brightest (at -5 km/s), is at only $2.7\sigma$ over three spectral channels, and was traced to a signal from a pair only of the 11 observing nights. The broad features are residuals from the running-average subtraction process, arising from broad lines of Galactic clouds from different nights. A detail spectrum (Figure 2) shows the very flat baseline achieved near Pluto’s velocity, while a test made by blanking a broader region (20 channels instead of 12) showed a change in integrated brightness of only around 10 %. This argues for a robust signal measurement of the narrow line, and also implies that broad line wings are faint.

The CO line from Pluto was independently detected in both the 2009 and 2010 epochs, at levels of $3.9\sigma$ and $5.4\sigma$ respectively, and with the same integrated brightness within the errors (Figure 2, right panel). The antenna temperatures are calibrated to about 20 %, based on rms scatter of the line-peak signal of spectral standards taken every night on the nearby source OH17.7-2. Also, inclusion of the two nights when Pluto had approached within $1.5^\circ$ of the Galactic Plane. These spectra show ripples and complex baselines, degrading the final line profile. The weight of these rejected data represent only 15 % of the total observations made.

The observations were planned to maximise the height of Pluto from the Galactic Plane, which varies as seen from the Earth, to minimise contamination problems. Pluto’s Galactic latitude in 2009 was +2.2°, and in 2010 was -2.0° to -1.7°, with longitudes of $\approx +12^\circ$. Using two periods well spaced around the year (Aug and Apr/May) also caused large changes in Pluto’s velocity relative to the telescope, from +26 km/s in 2009 to -27 to -19 km/s in 2010. Thus any narrow line seen persistently at Pluto’s velocity in the co-added data can only be from the planetary atmosphere, as any Galactic background emission is different every night. Galactic lines were seen around Pluto’s velocity in the spring data, but were much broader than the Pluto line.

hours in 2009 and 2010 respectively, with individual observations lasting approximately 20 minutes. The observing mode was frequency-switching, with a throw of 35.5 km/s within the passband. The telescope tracked Pluto’s sky position but not its velocity, so spectra were shifted in software to the dwarf planet’s reference frame. The spectrometer channel spacing was set to 0.04 km/s and there are systematics of around ±0.025 km/s for velocity-drifts of Pluto within each observation that have not been corrected. Data are shown on the main-beam antenna temperature brightness scale, with a beam efficiency of 0.75 at 230.538 GHz frequency.

For each night of data, the shifted spectra were co-added, and then the appropriate positive and negative frequency-switched features were averaged. The region of the net positive line was blanked and replaced with a linear interpolation of surrounding channels. A running average over 12 channels was then generated from this and subtracted from the pre-blanked spectrum as a baseline. The 11 nightly spectra made in this way were finally combined, weighted by $1/\text{noise}^2$ factors to take into account their different conditions and observing durations. Rejected data include two earlier nights using a smaller frequency-switch, and two later
nights of early data taken with a smaller frequency-switch was found to reduce the final integrated line intensity by \( \approx 20\% \). The brightness measurements could be affected by broad structure in the baseline, and Figure 3 demonstrates the spectrum obtained if the data are co-added without baselining. The curvature due to Galactic residuals makes it difficult to establish the nature of faint line wings.

The integrated antenna temperature of CO J=2-1 over 8 spectral channels (0.32 km/s) is 6.3±1.0 mK km/s on a main-beam brightness temperature scale. The mean \( T_{\text{mb}} \) is 20 mK, and the 1\( \sigma \) noise per 0.04 km/s spectral channel is 8.6 mK (twice as deep as Bockée-Morvan et al. 2001 for a common spectral resolution). The full-width at half-maximum intensity is approximately 0.28 km/s. The velocity centroid is \( \approx +0.07 \pm 0.055 \) km/s, including errors from comparing adjacent half-line intensities of 0.03 km/s and systematics of the 0.04 km/s channel spacing and \( \pm 0.025 \) km/s/velocity drifts within scans. Hence, the centroid velocity may be marginally positively offset from Pluto.

Figure 2 also shows the CO J=2-1 spectrum obtained in 2000 by Bockée-Morvan et al. (2001). Their \( T_{\text{mb}} \) values have been scaled downwards by a factor of four, to account for the greater beam-dilution for a compact source with the JCMT 15m versus the IRAM 30m telescope. On this ‘JCMT-equivalent’ scale, the 2000 spectrum has a \( \sigma \) upper limit of 7.5 mK in each 0.10 km/s channel, and the brightest channel near zero velocity is 7 mK. Weak positive signals were seen in line wings, and the integrated signal over \( \pm 1.3 \) km/s was 5.9 mK km/s, at signal-to-noise ratio of 4.5. The integrated intensity appears similar in 2000 and 2009/10, but the earlier spectrum has a greater contribution from possible line wings (Figure 2). A Voigt-profile fit to the new spectrum suggests broad wings now contribute \( \lesssim 35\% \).

### 3.1 Features of the CO spectrum

Figure 2 shows that the line-centre emission in 2009/2010 significantly exceeds that in the observation from April 2000 (Bockée-Morvan et al. 2001). In the brightest 0.1 km/s channel, the signal was 7 ± 2.5 mK, compared to 27 ± 5 mK now when averaged over the same region from the JCMT spectrum. Thus the ratio is at least 22/10.5 from the 1\( \sigma \) bounds, implying the line-centre intensity has more than doubled over a decade.

The core of the line now seen is narrower than previously predicted in models (Stansberry et al. 1994; Strobel et al. 1996). Model line profiles as plotted by Bockée-Morvan et al. (2001) are over twice as wide as observed, with full-width half-maxima of approximately 0.7 km/s. These models had atmospheric temperatures of 80-106 K, but our measured line width of 0.28 km/s implies that thermalised CO can not be warmer than \( \approx 50\) K. This estimate includes only thermal broadening, and so the gas could be even cooler if there is another source of velocity dispersion. Person et al. (2008) find evidence for large-scale atmospheric waves, but with horizontal wind speeds of under 3 m/s, while upwards sublimation flows should be at only a few cm/s (Toigo et al. 2010). The latter would also be in the contrary sense to the tentative red-shift noted above, since upwelling would produce a blue-shift from the near-side of the atmosphere that is preferentially observed.

### 4 DISCUSSION

The marked increase in CO line-peak brightness could be due to recent sublimation of surface ice – for example, the largest bright patch seen on Pluto’s surface is attributed to carbon monoxide frost (Buie et al. 2010). While this is a long-term feature in albedo maps, it could be a rich source of sublimating CO. Alternatively, a large expansion in isobar heights was detected between 1988 and 2002 (Elliot et al. 2003a), and such increases in atmospheric pressure could raise the effective emitting area for trace molecules. However, these occultation data only detect the atmosphere up to around 135 km (Young et al. 2008, e.g.), so effects at higher altitudes are uncertain. Regarding timescales, marked surface changes have occurred over intervals as short as a year (Buie et al. 2010b), while vertical sublimation speeds (Toigo et al. 2010) imply a molecule could rise thousands of kilometres within a decade. Hence it is reasonable that temporal changes in gas densities and/or abundances as surface ices sublimate could result in the CO lines being quite different over observations a decade apart (Figure 2).

Finding cold CO points to gas at very large heights – for example temperatures as low as 50 K have been predicted for about 4500 km above the centre of Pluto (Strobel 2008). This is under solar minimum conditions, as actually present in 2009/10. If the top of the CO layer is at 4500 km, then the atmosphere would subtend a diameter of 0.4 arcsec, as it was seen in 2009/10 with Pluto at 31 AU from the Earth. From this, in the simplest approximation of a filled opaque shell of CO molecules thermalised at 50 K, the beam-filling factor would be \( 3.6 \times 10^{-4} \), giving an expected line brightness of 18 mK. This is in good agreement with our mean \( T_{\text{mb}} \) of 20 mK. Lower atmospheric layers should be warmer and so add line brightness, but as an example, gas twice as hot (100 K) is predicted to lie below 2000 km (Strobel 2008), and thus be five times more beam-diluted.

#### 4.1 Comparison to models

Exact calculations for the CO line profile require radiative transfer calculations and an atmospheric model, beyond the scope of this Letter. However, some estimates can be made for the heights of the emitting layers. The density profile should decline approximately as a power-law (Strobel 2008), if CO has a constant mixing ratio with N\(_2\). Then the height below which the CO emission becomes opaque can be estimated, or more strictly, the height of the tangent where the column of CO molecules excited to the J=2 level produces \( \tau dv \approx 1 \times \Delta v \), for opacity \( \tau \) of unity and \( \Delta v \) equal to the line FWHM of 0.28 km/s. In an isothermal 50 K approximation, this height is 2750 km for a power-law density profile approximating that at solar maximum (Strobel 2008), and 2250 km for a solar minimum profile. The respective heights which contribute opacity of 0.01 are about 4600 and 3200 km. These values are for CO:N\(_2\)=0.005, following Strobel (2008) and at an upper limit observed in July 2009 (Lellouch et al. 2010). If contributions to the CO signal come from as high up as 4500 km, as estimated above from beam-filling arguments, then it appears that atmospheric densities must be at the high end of the models, or upper-level CO must be more abundant than assumed. Also, in the models high densities are associated with warmer temper-
ices. Pluto’s rapidly changing and fragile atmosphere could last a decade, in parallel to major alterations of the surface. There have been large temporal changes in the CO line profile over the last decade, and during the 2015 flyby.

Carbon monoxide is confirmed in the atmosphere of Pluto, and gives the first detection of high-altitude gas. There have been temporal changes in the CO line profile over the last decade, in parallel to major alterations of the surface. Pluto’s rapidly changing and fragile atmosphere could provide an interesting test-bed for models of global climates.

5 CONCLUSIONS

Carbon monoxide in the atmosphere of Pluto, and gives the first detection of high-altitude gas. There have been large temporal changes in the CO line profile over the last decade, in parallel to major alterations of the surface ices. Pluto’s rapidly changing and fragile atmosphere could provide an interesting test-bed for models of global climates.

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