FIRST DETECTION OF CARBON MONOXIDE IN THE ATMOSPHERE OF URANUS

Th. Encrenaz[1], E. Lellouch[1], P. Drossart[1],
H. Feuchtgruber[2], G. S. Orton[3], S. K. Atreya[4]
[1]LESIA, Observatoire de Paris, France, [2]MPIE, Garching, Germany,
[3]JPL, Pasadena, California, USA, [4]University of Michigan, USA

Carbon monoxide has been detected for the first time in the atmosphere of Uranus, from infrared spectroscopy using ISAAC at the VLT. This result provides new constraints on the planet's interior, and illustrates significant differences between the two "icy giants", Uranus and Neptune.

Why are Uranus and Neptune so different? Among the four giant planets, both share the common status of "icy giants", which refers to their global composition, mostly made of an icy core. This icy core accreted only a small fraction of protosolar gas. In contrast, in the case of the "gaseous giants" Jupiter and Saturn, this protosolar component, mostly made of hydrogen and helium, was predominant.

We could thus expect that Uranus and Neptune, with their similar sizes and comparable densities, would be sister planets. However, the planets exhibit remarkable differences in many ways. First, Neptune has a strong internal energy source while Uranus shows no evidence for it. In addition, Neptune's atmosphere exhibits an intense dynamical activity (shown, in particular, by strong temporal morphological variations), while Uranus is much more sluggish. Last but not least, both carbon monoxide CO and hydrogen cyanide HCN were found in large abundances in Neptune's stratosphere, while these species could not be detected so far in Uranus (Rosenqvist et al., 1992, Marten et al., 1993). CO, in particular, is about a thousand times more abundant in Neptune's stratosphere (with a mixing ratio of 10^{-6} with respect to hydrogen) than in Jupiter's atmosphere (Bézard et al., 1992), while its stratospheric abundance in Uranus is at least 30 times lower than the Neptune value. Marten et al. (1993) suggested that convection might be inhibited in Uranus' interior, preventing CO (as well as other species like HCN and phosphine PH_3) to come from the interior.

The detection (or non-detection) of CO and PH_3 in the tropospheres of both Uranus and Neptune would be a good test of this hypothesis. Phosphine, in particular has been detected in large abundances (larger than expected by out-of-equilibrium thermochemical models) in both Jupiter and Saturn; these large amounts are attributed to convective motions which bring up PH_3 from the deep interior up to observable atmospheric levels of a few bars or less. Searching for PH_3 in Uranus and Neptune, however, is more difficult, because phosphine is expected to condense at a level of about one bar.

Observations at the VLT

The 5-µm spectral window offers a good opportunity for probing the deep atmosphere of giant planets, because this range is free of methane absorption. In the case of Uranus and Neptune, the 5-µm radiation is expected to come from above a cloud deck located at about 3 bars, presumably made of H_2S ice (Baines et al., 1995).

Observations were performed in October-November 2002 with the ISAAC (Infrared Spectrometer And Array Camera) instrument mounted at the VLT-UT1 (Antu). We used the long-slit mode of the instrument (Cuby et al., 2000) in the long-wavelength mode, with a slit height of 120 arcsec and a slit width of 2 arcsec, corresponding to a resolving power of 1500. Using two different grating positions, we covered the 4.60–5.00 µm range. Data were reduced using the Eclipse software (Devillard, 1997) and the IRAF standard package. The star HR 8293 was used for calibration.

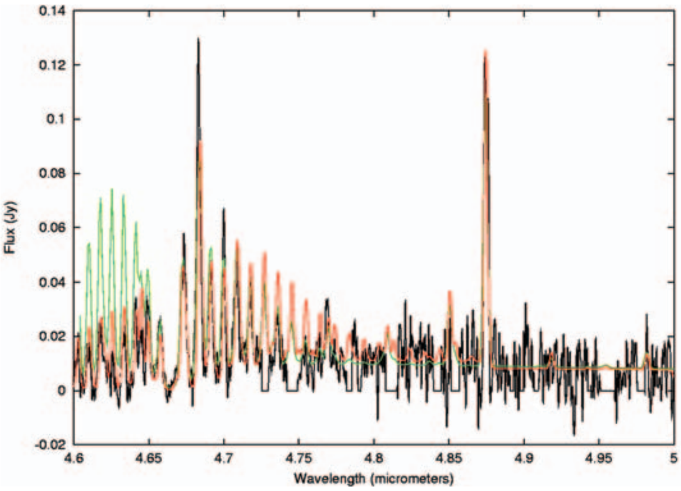
Figure 1 shows the calibrated spectrum of Uranus, obtained from dividing the raw spectrum of Uranus by the stellar spectrum (Encrenaz et al. 2004). Data have been replaced by zeros in the spectral regions of strong telluric absorption. In order to recover the information contained in these spectral ranges, we multiplied, in the modelling phase, the synthetic spectrum of Uranus by a model spectrum of the Earth atmospheric absorption, and the result was convolved to the atmospheric function. The telluric absorption spectrum was validated by comparison with the star spectrum.

Figures 1 and 2 show that the observed spectrum of Uranus is the sum of three components. The first one consists of a few strong emission lines due to the H_3^+ ion (especially at 4.684 and 4.875 µm), already detected previously in Uranus's upper atmosphere (Trafton et al., 1993, 1999; Encrenaz et al., 2003). We attribute the second, unexpected component to a set of CO emission lines which can all be attributed to the J-components of the CO(1-0) band, from R7 to P8 (4.60-4.73 µm). Two mechanisms can be considered a priori to explain the emission: fluorescence or thermal emission in the stratosphere. Modelling the thermal CO(1-0) emission shows that the fit with the data is not satisfactory, for any value of the rotational temperature. Even for a low temperature (T= 150 K), the fit with the data is very poor as shown in Fig. 1, and this fit would be even worse for higher temperatures. The thermal emission mechanism has thus to be excluded, and fluorescence has to be favoured. Finally, the third component appears as a weak continuum between 4.75 and 5.00 µm. We attribute this continuum to solar reflection above the the cloud level at 3 bars, presumably due to H_2S ice.

Modelling and Interpretation

The fluorescence emission of CO in Uranus was calculated using a code derived from the fluorescence of CH_4 in Jupiter and Saturn which successfully reproduces the observed methane emission at 3.3 µm (Drossart et al., 1999). Calculations show that, because the CO-H_2 collision rate is very low, non-LTE effects start to play a role at relatively low altitudes, around the tropopause at 100 mbar, and become predominant above the 10 mbar level. This situation is very different from the case of the methane fluorescence in the giant planets, because the CO-H_2 collision

Figure 1: The calibrated spectrum of Uranus (black line). Red line: best-fit model, including CO fluorescence, H_3^+ emission and tropospheric emission. Green line: three-component model with CO fluorescence replaced by CO thermal emission at 150 K, normalised at 4.71 μm.



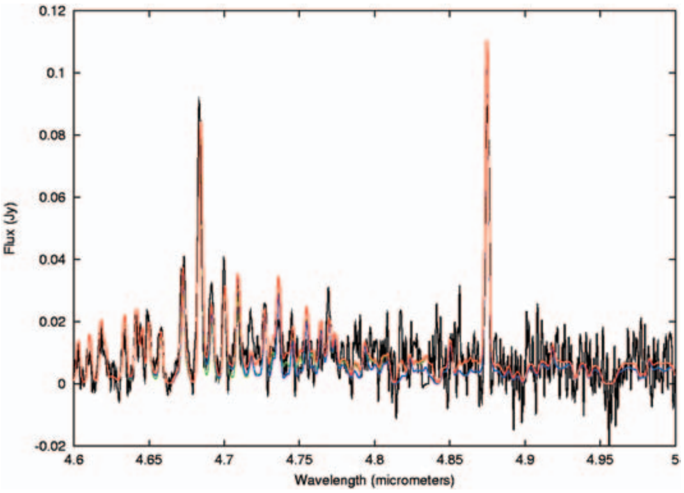


Figure 2: The raw (undivided) spectrum of Uranus (black line) compared to different synthetic models multiplied by the atmospheric transmission function. Red line: best-fit model (CO = PH_3 = 0). Green line: CO = $2\ 10^{-8}$, PH_3 = 0. Blue line: PH_3 = $1\ 10^{-6}$, CO = 0.

rate is about 100 times smaller than the CH_4-H_2 rate (which is predominant in Jupiter and Saturn's stratosphere, because CH_4 condensation does not take place in these planets, whereas it does in Uranus and Neptune). As shown in Fig. 2, a good fit of the fluorescence emission of CO in Uranus is obtained for a mean constant CO mixing ratio of $3\ 10^{-8}$. We note that the CO fluorescence probably takes place predominantly in the region 0.1–1 bar.

Figure 2 also shows a comparison of the data with various models of the reflected tropospheric component, assuming different mixing ratios of CO and PH_3 in the deep troposphere of Uranus. It can be seen that the best fit is obtained where no CO or PH_3 are present; upper limits are inferred, corresponding respectively to $2\ 10^{-8}$ for CO and 10^{-6} for PH_3. For comparison, we note that, in the case of Jupiter and Saturn, the CO mixing ratios inferred from the data are about 1–2 10^{-9}; the measured PH_3 mixing ratios are $6\ 10^{-7}$ and 2-6 10^{-6} respectively.

We now have three different constraints to reconcile: (1) The upper limit inferred from the millimeter data implies that the CO mixing ratio is less than $3\ 10^{-8}$ in the stratosphere, i.e. above the 100 mbar pressure level; (2) the fluorescence emission of CO analysed in the present study is consistent with a CO mixing ratio of $3\ 10^{-8}$ in the 0.1–1 bar pressure range, i.e. in the upper troposphere; (3) from the fit of the tropospheric continuum in our data, we infer that the CO mixing ratio is less than $2\ 10^{-8}$ in the lower tropopause, above the 3 bar level.

It should be noted first that there is a large uncertainty (by a factor of about 2) in the CO abundance derived from our fluorescence model, which prevents us from deriving firm conclusions about the CO vertical distribution. However, if the numbers given above were to be confirmed, the only interpretation would be that the CO mixing ratio is not constant throughout the atmosphere of Uranus. This would probably imply that CO is, at least in a large fraction, of external origin. Indeed, if CO were of internal origin, we would expect its mixing ratio to be constant up to the upper stratosphere. As in the case of H_2O, detected in the stratospheres of all giant planets with the ISO satellite (Feuchtgruber et al., 1997), the CO external source could come either from icy satellites or from interplanetary meteorites.

Let us note finally that the upper limits of CO and PH_3 inferred in the deep troposphere of Uranus suggest that, as proposed by Marten et al. (1993), convection might be locally inhibited in the interior of Uranus, leading to the absence of vertical transport and dynamical activity. The origin of this inhibition, probably connected to the absence of internal heat in Uranus, remains to be understood.

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