# The Detection of Carbon Monoxide Gas Emission in (2060) Chiron

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**2060 Chiron is among the small population of large, outer solar system objects called Centaurs. Chiron's unusual, 51-year orbit ranges in distance from 8.5 to just over 19 AU, and exhibits an inclination to the ecliptic plane of 8.5 degrees. Recent dynamical studies[1,2] show this orbit is unstable to giant planet perturbations on timescales of $< 10^6$ years, indicating that it is a recent addition to the planetary region. This, along with its low inclination orbit, and its size similarity to the newly-discovered population of 100-400 km diameter Kuiper Disk objects[3,4], provides strong circumstantial evidence that Chiron is an escaped object from the Kuiper Disk. Chiron's present orbit subjects it to much more intense insolation than objects in the Kuiper Disk experience. That insolation generates surface activity, as revealed by a highly-variable coma[5,6,7]. The source of Chiron's activity has been speculated on for many years[8] but never observationally identified. We report here the detection of CO molecules in Chiron's coma, which are probably the sublimation agent generating Chiron's activity.**

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Chiron's coma was first resolved in CCD images[6] that revealed the presence of Mie **or molecular** scattering particulates surrounding the object at distances as far as $2 \times 10^5$ km from the nucleus. The initial evidence for gas in Chiron's coma was obtained by the spectroscopic detection of the efficiently-fluorescing tracer radical, CN[9]. However, CN is a dissociation fragment and not a parent molecule, so its scientific usefulness is somewhat limited. No other chemical species have been detected in Chiron's coma. Recently, however, Chiron's coma was photometrically probed by means of a stellar occultation, and clear evidence was obtained for collimated, optically thin particulate structures[10]. These structures suggest the presence of escaping jets and suborbital arches, presumably emanating from discrete sites on Chiron's nucleus. If this interpretation is correct, it confirms arguments[11] which suggest that Chiron's activity may be generated by a low-gravity analog to the geyser-like vents that Voyager 2 observed on Neptune's large satellite Triton.

Chiron's activity has been puzzling because the comet is so far from the Sun. Presently, for example, Chiron is near its perihelion over 8.5 AU from the Sun (1 AU equals the average distance from the Earth to the Sun). Varying levels of activity detected in Chiron from 1988 to 1993 occurred while the object was between 9 and 11 AU from the Sun. Conditions at these distances are too cold for $H_2O$ and $CO_2$ ices to sublimate, which generate the comae of most comets in the inner solar system. Further, the clear evidence of activity detected in archival images of Chiron made from 1969 to 1972,[7], while Chiron was near aphelion at 19 AU, provide additional evidence that its activity is not driven by $H_2O$-ice or $CO_2$-ice sublimation. Indeed, because only a few cosmogonically abundant molecules have sufficient equilibrium vapour pressures to vigorously sublimate at distances of 8 to 19 AU from the Sun, one suspects that Chiron's gas coma is generated by one of the very few, relatively-abundant low-temperature sublimators called supervolatiles, such as CO, $N_2$, $CH_4$, or possibly $S_2$[8,12].

Because (i) CO's molecular constants make it easier to detect than $CH_4$, $N_2$, and $S_2$, and (ii) CO is more abundant in comets than are the other supervolatiles[12], we were motivated to undertake a search for CO as the source of Chiron's activity.

The search technique we employed was to attempt the detection of CO through its well-known rotational bands at 1.3 mm (230 GHz) and 2.3 mm (115 GHz). Our search was carried out using multi-channel filterbank spectrometers on millimeter-wavelength telescopes in Hawaii and Arizona in 1994 and 1995.

Our first attempt at CO detection was made with a spectrometer that was tuned to CO's J=2-1 rotational transition at 230 GHz. These observations were made using the Caltech Submillimeter Observatory (CSO) 10.4 m telescope on Mauna Kea, Hawaii during 1994 Feb 25-26 UT. No detection was made, but a useful upper limit to the CO production rate from Chiron's coma of Q(CO) $< 5 \times 10^{28}$ $s^{-1}$ was obtained. ¿From this upper limit one can use previously published sublimation models for Chiron[11] to easily establish that any CO sublimation must be sporadic, or limited to a small fraction of the surface, or both.

We renewed the search for CO in Chiron's coma during 1995 June 10–12 UT using the National Radio Astronomy Observatory (NRAO) 12 m telescope on Kitt Peak, Arizona. The telescope's receiver consists of dual-channel, cooled SIS mixers, which were tuned to reject the image sideband. The backends were two 128-channel filterbanks, each with two polarizations. The two filterbanks used have spectral resolutions of 100 kHz and 250 kHz per channel, which correspond to velocity resolutions of 0.26 km $s^{-1}$ and 0.65 km s,$^{-1}$ respectively. Temperature scales were established in terms of $T_R^*/\eta_c$ by a standard chopper-wheel method. Data were obtained in the position switching mode; the main beam efficiency, $\eta_c$, was 0.84. The pointing accuracy of the telescope was measured to be $\sim 5''$ during the observing period and Chiron's ephemeris was estimated to be accurate to within 2 arcsec (D.J. Tholen, pers. comm.); this is very small compared to the half-power beamwidth of the telescope of $53''$ at 115 GHz.

The J=1-0 rotational transition of CO at 115 GHz was detected in both polarizations of each of the two different resolution spectra, resulting in four independent spectra which exhibit the 1-0 feature. The line is present in the spectra obtained for each day on June 10, 11, and 12, and maintains a consistent line width and intensity as the data are co-added and the signal-to-noise ratio increases. The spectra from each of the two parallel filterbank spectrometers, after coadding both polarizations, are shown in Figures 1 and 2. Although the S/N is somewhat low in the separate spectra, the simultaneous detection of this feature in both polarizations of both spectrometer backends provides four independent detections, and is strong evidence that the detection is real.

In order to verify that the CO feature we detected did not arise from a background galactic cloud, additional spectra were obtained at the CO J=1-0 frequency during 1995 Nov 17-19 UT, with the NRAO 12 m pointed at the sky coordinates that Chiron possessed on 10-12 June 1995. No sign of CO emission was detected, down to a 3-sigma limit of Tdv=0.007 K km $s^{-1}$. This indicates that the emission line seen in June 1995 did not arise from a cold background cloud. We also checked for the presence of systematically bad channels in the telescope's receiver that could have created a spurious detection at the frequency of the J=1-0 CO emission. This was done by co-adding spectra from unsuccessful searches for CO in many comets all at different velocities, which had the effect of slightly changing the frequency. No anomalous channels were detected at or within 20 channels of the location of the CO emission line, down to a limit of Tdv=0.003 K km $s^{-1}$.

At the time of the June 1995 observations, Chiron had a heliocentric distance of $D$=8.5 AU and a geocentric distance of $\Delta$=8.4 AU. Our analysis of the higher-resolution 100 kHz spectrum indicates that the CO feature was marginally resolved in this filter bank with a FWHM width of 150$\pm$100 kHz, corresponding to a velocity width of 0.39 $\pm$ 0.26 km $s^{-1}$. **We cannot be sure that the line is resolved with either spectral resolution. The line is detected only across two channels, which is close to the Rayleigh (Nyquist) criterion. Thus we cannot resolve any line structure in the profile.** Although this is large compared to the $\sim$0.1 km $s^{-1}$ thermal velocity of pure CO gas freely sublimating at 8.5 AU, it is in *good* agreement with the coma model predictions for a *dusty* CO coma surrounding Chiron[13].

At our velocity resolution of $\approx$0.3 km $s^{-1}$, no measurable redshift or blueshift of the CO feature from the predicted geocentric velocity of Chiron was observed. This indicates that to within our velocity resolution, the CO molecules in Chiron's coma at the time of these observations were not strongly beamed along or away from the Chiron-Sun line (which is roughly coincident to the Chiron-Earth line).

The grand-average line flux areas and corresponding CO column densities (N) and production rates (Q) for Chiron's coma derived from each of our two observing runs are given in Table 1. These calculations assume that the CO emission fills the telescope beam size of 53 $''$. If the CO emission region is smaller than this, then the values for the column density and production rates will be higher. A total CO column density of N(CO)=(9$\pm$4) $\times$ $10^{12}$ $cm^{-2}$ was calculated for the June 1995 data, assuming an optically thin gas and a rotational temperature of 10 K, as is expected from CO observations of other distant, active comets[14]. A production rate of Q(CO)=(2$\pm$ 1) $\times$ $10^{28}$ $s^{-1}$ was calculated using a photodissociation decay model,[15] assuming that the CO sublimates directly from the nucleus with a velocity of 0.2 km $s^{-1}$ (equal to half the estimated linewidth). An independently estimated production rate of CO assuming the simple, isotropic expansion of molecules through the telescope beam is Q(CO)=(0.9 $\pm$ 0.5)$\times 10^{28}$ $s^{-1}$. Averaging these two production rate estimates, we obtain an estimated CO production rate of Q(CO)=(1.5 $\pm$ 0.8)$\times 10^{28}$ $s^{-1}$. This can be compared to the upper limits to the CO J=2-1 emission we obtained in February 1994, corresponding to N(CO) <(3$\pm$ 1)$\times 10^{13}$ $cm^{-2}$, and Q(CO)<5$\times$ $10^{28}$ $s^{-1}$.

The simplest origin for the CO gas detected in Chiron's coma is from the direct sublimation of solid state CO on, or in thermal contact with, Chiron's surface. The sublimation of a pure CO-ice surface completely covering Chiron is estimated to generate $\approx 3\times 10^{31}$ CO molecules per second[11]. Our observation of Q(CO)$\sim 1.5\times 10^{28}$ $s^{-1}$ indicates that $<5 \times 10^{-4}$ of Chiron's surface area is sublimating. If concentrated in one area, this would correspond to a circular spot with a radius of just 4 km($R_{chiron}$/90 km)$^2$, where $R_{chiron}$ is Chiron's true radius (90 km is the best present radius estimate[3]). Of course, several smaller spots distributed on the surface with a combined active area near this estimate would also suffice. Although uncertainties in Chiron's surface emissivity and radius could change the estimated active surface fraction by a factor of several, the detected CO column and production rate clearly indicate that much less than 1% of Chiron's surface is freely sublimating CO.

The fact that the estimated production rate of CO derived from our mm-wavelength detection corresponds to one or more very small sublimating patches, as opposed to a large fraction of the surface, suggests that the narrow, highly-localized particulate plumes and archlike structures described in the stellar occultation experiment[10] may be CO-driven vents or geysers. This inference is supported by the surprisingly-warm surface temperature measurements of Chiron[3]. Given the small apparent sublimation fraction of the surface derived above, it now becomes clear why Chiron's surface is found to be so much warmer than a broadly-distributed surface sublimation would predict. Latent-heat cooling of the surface is restricted to a surface area fraction far less than 1%, so most of the surface will reach radiative equilibrium temperatures near 100 K, as observed,[3] rather than the ~35-55 K temperature indicative of a uniformly-sublimating surface consisting of CO or another of the supervolatiles (e.g., $N_2$, $CH_4$).

The detection of CO in 2060 Chiron means that the source of activity in both of the well-known, routinely active comets beyond 4 AU (Schwassmann-Wachmann 1[16] and 2060 Chiron) is related to CO sublimation. This, and the discovery[17] of CO emission from the distant comet Hale-Bopp near 8 AU suggests that CO sublimation is a common source of distant cometary activity.

Because CO is sufficiently volatile to sublimate throughout Chiron's orbit, including at aphelion near 19 AU, there is at present no requirement to invoke other supervolatiles to explain Chiron's historical activity[11]. Having said this, however, we must stress that our observations do not rule out additional subliming supervolatiles on Chiron. In that regard, the search for $N_2$ in Chiron's coma (or on its surface) is fundamental if we are to place Chiron (and the presumably related Kuiper Disk objects in the trans-Neptunian region) in a broader context of outer solar system cosmochemistry. Recall that Chiron and the similarly-sized Kuiper Disk objects are logarithmically intermediate in scale between short period comets (with radii of 10 km and less) and Pluto/Triton (with radii of 1150-1350 km). All of these objects are thought to have originated in the region between 20 and 50 AU[18]. However, whereas the surface ices and atmospheres of Triton and Pluto are dominated by $N_2$, with only a trace of CO[19], cometary comae exhibit $CO/N_2 >> 1$. The origin of this chemical dichotomy is not understood[12,20]. We suggest that an important clue to the nature of Chiron and its largish cohorts lies in whether the $CO/N_2$ ratio of Chiron and related-type objects in the trans-Neptunian region is comet-like, or Pluto/Triton-like.

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**Table 1**
**Observations of CO in Chiron**

| Dates (UT) | CO Line | $T_R$dv (K km $s^{-1}$) | N(CO) $cm^{-2}$ | Q(CO) $s^{-1}$ |
|---|---|---|---|---|
| 1994 Feb 22–24 | J=2–1 | $<0.012\pm0.004$ | $<(3\pm 1)\times 10^{13}$ | $<(5.0\pm 2.5)\times 10^{28}$ |
| 1995 Jun 10–12 | J=1–0 | $0.0135\pm0.0027$ | $(9\pm4)\times 10^{12}$ | $(1.5\pm0.8)\times 10^{28}$ |

## Figure Captions

Figure 1. Spectrum of the carbon monoxide J=1-0 rotational transition in 2060 Chiron with 100 kHz (0.26 km $s^{-1}$) spectral resolution obtained June 10-12 1995 UT at the NRAO 12 m. The frequency scale shown is referenced to Chiron's velocity, so an isotropic CO emission would produce a feature at zero MHz. The spectrum is a result of 110 co-added scans of 6 minutes each, with a total position-switched integration time of 39600 sec. The line is seen in both polarizations of the data and is present in the spectra obtained on each day June 10, 11, and 12, and maintains a consistent line width and intensity as the data are co-added and the signal-to-noise ratio increases.

Figure 2. Same as Figure 1, for the co-added, lower-resolution 250 kHz (0.65 km $s^{-1}$) dataset, which was obtained simultaneously with the 100 kHz data. Although the CO feature is not resolved here, both its predicted width and the width observed in Figure 1 indicate it would not be expected to be resolved at 250 KHz resolution. The detection of the CO feature in both polarizations of both spectrometer backends is strong evidence that the detection is real.

## References


1. Levison, H.F., & Duncan, M.J., 1994. Icarus, 108, 18.

2. Dones, L., Levison, H.F., & M.J. Duncan, 1996. In *Completing the Inventory of the Solar System* (T. Rettig & J. Hahn, eds.), ASP Vol. **107**, 233.

3. Campins, H., C. Telesco, D. Osip, G. Rieke, M. Rieke, & B. Schultz, 1994. AJ, 108, 2318 .

4. Jewitt D.C., & J.X. Luu, 1995. Astron. J., 109, 1867.

5. Hartmann, W.K., Cruikshank, D.P., & D.J. Tholen, 1989. Icarus, 83, 1.

6. Meech, K.J., & M.J.S. Belton, 1990. AJ, 100, 1323.

7. Bus, S.J., et al., 1993. *Proceedings of the Distant Comet Activity Workshop*, Lenggries, Germany (H.U. Keller and W. Huebner, eds.), 41.

8. Stern, S.A., 1989. PASP, 101, 126.

9. Bus, S.J., et al., 1991. Science, 251, 774.

10. Elliot, J.L., et al., 1995, Nature, 373, 46.

11. Stern, S.A., Jackson, A.A., & D.C. Boice, 1994. AJ, 107, 765.

12. Mumma, M.J., Weissman, P.R., & S.A. Stern, 1993. In *Protostars and Planets III* (E.H. Levy and J.I. Lunine, eds.). Tucson, Univ. of Arizona Press, 1177.

13. Boice D.C., et al., 1993. In *Proceedings of the Distant Comet Activity Workshop*, Lenggries, Germany (H.U. Keller and W. Huebner, eds.), 134.

14. Crovisier, J., et al., 1995. Icarus, 115, 213.

15. Haser, L., 1957. Bull. Acad., Sc. Liege, 43, 740.

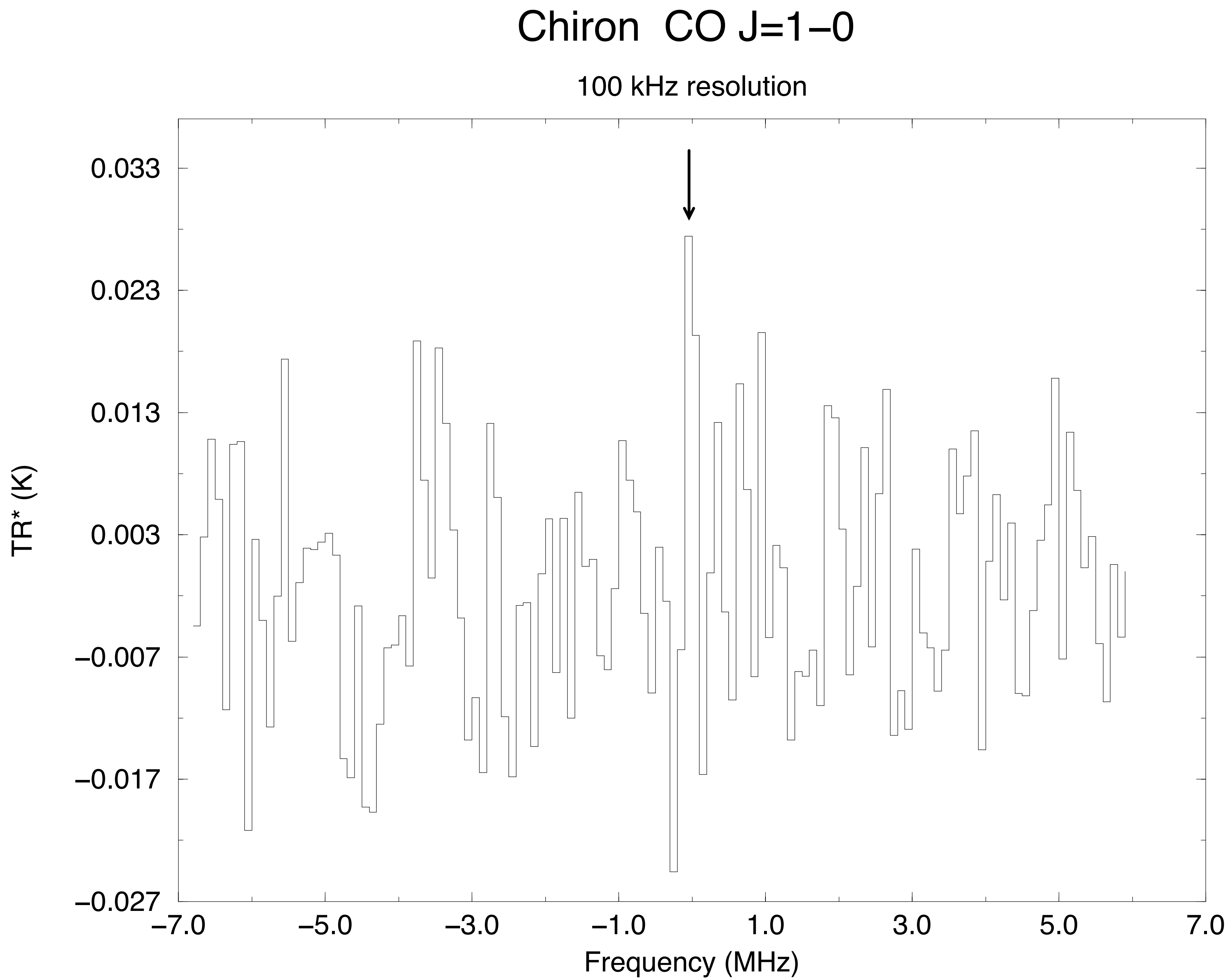
16. Senay, M.C., & D.C. Jewitt, 1994. Nature, 371, 229.

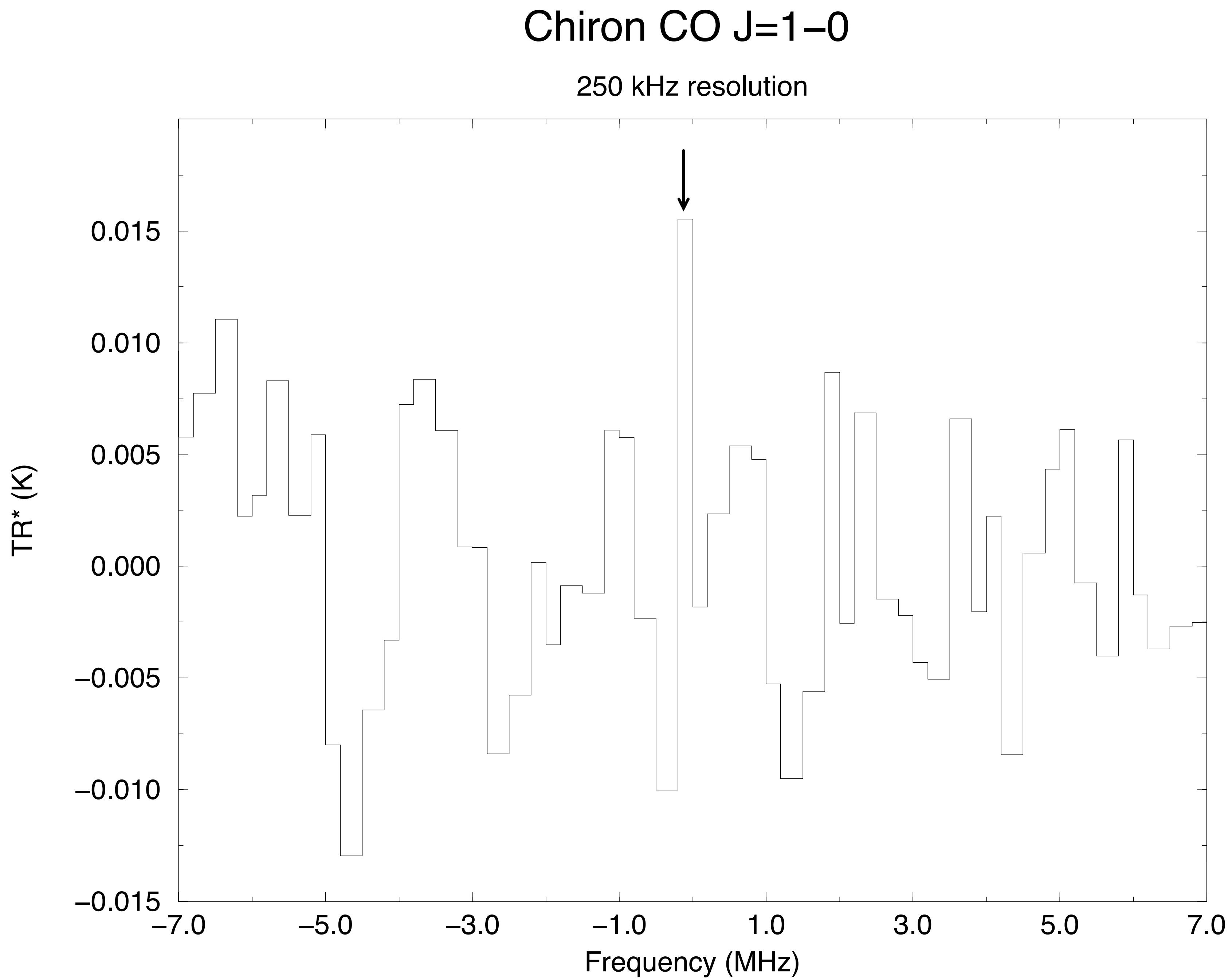
17. Matthews, H.E., D. Jewitt, & M.C. Senay, 1995, IAU Circular, **6234**

18. Weissman, P.R. & H.F. Levison, 1997. In *Pluto & Charon* (S.A. Stern and D.J. Tholen, eds.), Tucson, Univ. of Arizona Press, 559.

19. Cruikshank, D.P., et al. 1997. In *Pluto & Charon* (S.A. Stern and D.J. Tholen, eds.), Tucson, Univ. of Arizona Press, 221.

20. Lunine, J.I., S.K. Atreya, & J.B. Pollack, 1989. In *Origin and Evolution of Planetary and Satellite Atmosphere* (S.K. Atreya, J.B. Pollack, and M.S. Matthews, eds.). Tucson, Univ. of Arizona Press, 605.


Chiron CO J=1−0
100 kHz resolution
TR* (K)
0.033
0.023
0.013
0.003
−0.007
−0.017
−0.027
−7.0
−5.0
−3.0
−1.0
1.0
3.0
5.0
7.0
Frequency (MHz)


Chiron CO J=1–0
250 kHz resolution
TR* (K)
0.015
0.010
0.005
0.000
–0.005
–0.010
–0.015
–7.0
–5.0
–3.0
–1.0
1.0
3.0
5.0
7.0
Frequency (MHz)