# Millimetric and optical observations of Chiron*

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*: Based on observations collected at the European Southern Observatory, La Silla, Chile (prop. 56F.-0464), and at the Institut de Radio Astronomie Millimétrique 30-m telescope, Pico Veleta, Spain

# 1 Abstract

2060 Chiron has shown activity at heliocentric distances larger than 11 AU. To investigate the nature of the activity in this peculiar object, we observed Chiron during its approach to perihelion from June 1995 to January 1996. Observations at millimetre wavelengths were made at the IRAM 30-m telescope in June, September, and November 1995. Emission lines of CO, HCN, $H_2CO$ and $H_2S$ were searched for. On 25-28 January 1996, we obtained spectra of Chiron with the 2.2-m telescope at ESO, La Silla, from 3550-4750 Å to search for possible emission features, for example, CN. No molecular signal was detected. Upper limits on the gaseous species observed are presented.

## 2 Introduction

2060 Chiron (95 P/Chiron) has shown an extended dust coma in optical images at large heliocentric distances (r $\approx$11 AU) (e.g. West, 1991). Although activity has now been observed in several comets at heliocentric distances larger than 4 AU, its origin is still puzzling. At such distances from the Sun, temperatures are too low for significant water ice sublimation from the nucleus. Therefore, more volatile molecules such as CO and $CO_2$ are thought to be the main species driving the activity. In addition, the phase transition from amorphous to crystalline ice is proposed to provide a source of activity. However, direct measurements of the evaporating gas in distant comets are still sparse.

Chiron reached perihelion, at r = 8.5 AU, on 14 February 1996. With decreasing heliocentric distance, it was expected that increasing activity would be observed, allowing measurements of gas emissions. Such observations could give a clue to the nature of the activity-driving species. So far, only the daughter product, CN, has been detected in Chiron during an outburst in January 1990 (Bus et al., 1991), and the detection of CO was announced in June 1995 by Womack and Stern (1995).

To search for sublimating parent molecules, we concentrated on species with low sublimation temperature ($T_{subl}$) (e.g. CO ($T_{subl}$ = 24 K), $H_2S$ ($T_{subl}$ = 57 K), $H_2CO$ ($T_{subl}$ = 64 K) and HCN ($T_{subl}$ = 96 K)). Emission lines of these molecules were searched for with the Institut de Radio Astronomie Millimetric (IRAM) 30-m telescope, Pico Veleta, Spain, from June to November 1995. In addition, we searched for possible CN emission in the optical range at the 2.2-m telescope at European Southern Observatory (ESO), La Silla, Chile, in January 1996. No emission feature could be found in Chiron, neither in the millimetre range, nor in the optical. Upper limits are derived and their implications will be discussed.

## 3 Observations and Results at radio wavelength

Chiron was observed at millimetre wavelengths at the IRAM 30-m telescope in June, September and November 1995. The CO lines were searched for during all observing periods. In November 1995 additional volatile molecules (HCN, $H_2CO$, $H_2S$) were searched for. The spectra have been obtained with an autocorrelator with 20 kHz and 10 kHz resolutions, for the CO(2-1) and CO(1-0) lines, respectively, corresponding to 0.025 km $s^{-1}$. The observations were performed either in frequency switching mode or by beam switching by tilting the secondary mirror. The half-power beam width at 230 GHz was 10.4 arcsec. A log of the observations is given in Table 1.

No detection of gas emission lines could be made. Therefore, the spectra were used to derive $3\sigma$ upper limits for the species observed. Unfortunately, these limits are not as good as might have been expected, because of poor weather conditions during our observing periods.

Upper limits of fluxes have been converted to production rate limits with a model already used for other comets (Crovisier, 1987; Crovisier et al., 1991; Bockelée-Morvan and Crovisier, 1992), which includes both thermal and radiative excitation. We assume spherically symmetric outgassing, a coma temperature of 10 K and an outflow velocity of 0.5 km $s^{-1}$, as observed for P/Schwassmann-Wachmann 1 at 5.5 AU (Crovisier et al., 1995). Elliot et al. (1995) and Bus et al., 1996, propose jet features in Chiron's coma from a star occultation experiment. If asymmetric outgassing in narrow jets is assumed, the line width reduces, and thus, the upper limits derived are reduced accordingly. However, since nothing is known about the exact distribution of jets in Chiron's coma, we assumed the simplest case of symmetric outgassing. Photo-destruction scale lengths are taken from Crovisier (1994) and all observed species are assumed to be parent molecules.

Table 2 gives the derived upper limits for the areas of the CO(1-0) and CO(2-1) lines, together with the resulting upper limits for the CO production rate. Averaging all available spectra of the

CO(2-1) line, we obtain an upper limit of $1.0\times10^{28}$ s$^{-1}$ for its production rate from June to November 1995.

Table 3 shows the result of our search for other volatile species in the coma of Chiron (HCN, $H_2CO$ and $H_2S$).

# 4 Observations and Results at optical wavelength

Optical spectra were taken on 25-28 January, 1996, with the 2.2-m telescope at ESO using EFOSC 2. The spectra covered a wavelength range of 3550 Å – 4750 Å(see Table 1). The total field-of-view was 5.5×5.5 arcmin, with 0.66 arcsec/pixel, and 2.2 Å/pixel in wavelength direction. The slit width used was 1.5 arcsec, and the slit orientation was along the east-west direction.

An image of Chiron taken on 26 January 1996 (Fig. 1) at 06:04 UT with EFOSC 2 in the V-filter (exposure time: 300 s) shows a faint tail towards the anti-solar direction (position angle: 294°; phase angle 6.2°), indicating that the comet was indeed active during our observing period. Observations on 8 February 1996 by Campins and Rieke (1996) in the K band showed no coma.

The standard reduction procedures have been applied to all spectra obtained in January 1996. The sky background and night sky lines were removed by interpolating from areas at the edge of the frames along the slit. All frames obtained during the observing run in January 1996 were added to improve the signal-to-noise when searching for weak gas emissions. A solar analogue star (Hyade 64) was observed with the same slit width as the comet. To obtain an upper limit on the gas production rate, the solar spectrum (with the same resolution as the cometary spectrum) was fitted to Chiron's continuum and then subtracted. No emission feature could be found.

To compare with previous observations, we compute the root-mean-square (rms) pixel-to-pixel variations on the expected CN emission at 388 nm after binning the spectrum to a resolution of 4.9 Å/px. Table 3 gives our resulting $3\sigma$ upper limit on the line area of CN. This can be compared to the detection of 7.3 $10^{-16}$ erg cm$^{-2}$ s$^{-1}$ by Bus et al., 1991. The rms in our spectra (2.1 $10^{-17}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$) is comparable to the value by Bus et al. (1991) (2.2 $10^{-17}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$). In addition, Chiron's visual magnitude of 16 on 25-26 January, 1996, is comparable to its brightness in January 1990 (Luu and Jewitt, 1990). Thus, a CN activity of Chiron as observed in January 1990, should have been detected in our measurements.

Table 3 gives the upper limit on the production rate. We assumed as the simplest case, since no detection was made, a Haser model with a parent scale length of $5.9\times10^4$ km (at 1 AU), corresponding to the value used to derive the upper limit for the HCN production from radio observations, and a daughter scale length of $3\times10^5$ km from Cochran et al. (1992). All lengths have been scaled with the square of the heliocentric distance. The g-factor for CN fluorescence was taken from Tatum (1984). When comparing the derived production rate to Bus et al., it must be taken into account that they used a vectorial model. The line area is therefore best suited for a direct comparison of the measurements.

To obtain the reflectance spectrum of Chiron, its continuum was divided by the solar spectrum. Figure 2 shows the resulting reflectance spectrum, normalized to the reflectivity at 4600 Å. We compute the reflectivity gradient by using the defining formula given by Jewitt and Meech (1986).

$$S'(\lambda_1, \lambda_2) = (dS/d\lambda)/S_{4600}.$$

Table 4 gives the resulting reflectivity gradient for different wavelength ranges.

## 5 Discussion

Although 2060 Chiron seems to show continuously some level of activity, its activity has varied over the past 25 years (Marcialis and Buratti, 1993). Its magnitude dimmed from 1970 to 1985, followed by an outburst in 1989/90. During this outburst, CN emission could be detected (Bus et al., 1991), which is, so far, the only detection of CN in Chiron's coma.

It was expected that the increased solar flux at Chiron during approach to perihelion (on 14 February 1996) might increase the activity level. Crovisier (1993) has shown that radio spectroscopy — compared to ultraviolet and infrared spectroscopy — could be the most sensitive technique for detecting gas production in distant comets, in addition to optical spectroscopy. In this respect, it is worth noticing that the first gas species to be detected in comet C/1995 O1 (Hale-Bopp) were CN (in the optical; Fitzsimmons and Cartwright, 1996) and CO (at radio wavelengths; Biver et al., 1996; Jewitt et al., 1996) — at more than 6.5 AU. We therefore searched for gaseous activity in Chiron during the second half of 1995 and in January 1996 using millimetric and optical observations. However, no gas emission feature could be found. We now discuss the significance of the upper limits derived.

During 23-26 June 1995, we obtained upper limits on the production rate of CO from both, CO(1-0) and CO(2-1) lines. These values need to be compared to the claimed detection of CO(1-0) emission in Chiron on 10-12 June, 1995, (Womack and Stern, 1995) with a production rate of $4 \pm 2 \times 10^{28}$ $s^{-1}$. Our upper limit derived from the CO(1-0) line is in agreement with this observation, but the production rate upper limit derived from our CO(2-1) observation of $2.0 \times 10^{28}$ $s^{-1}$ is on the lower side of the range given by Womack and Stern (using a pure thermal model, as used by Womack and Stern, leads to similar results). If the excitation conditions in Chiron are as assumed in our model (based on the observations of comet 29P/Schwassmann-Wachmann 1), the (2-1) line gives a much more stringent limit on the sublimation of CO than the (1-0) emission. Comparing our upper limit with the measurement by Womack and Stern makes the proposed detection doubtful. However, we cannot completely exclude special excitation conditions in Chiron which would favour the (1-0) emission. Unfortunately, our limit on this line is rather high because of bad weather conditions in June 1995. The only other explanation for the disagreement in observations could be a significant drop in activity from Chiron in the two weeks between the observations. Averaging all CO observations obtained in the second half of 1995 we obtain an upper limit of $1.0 \times 10^{28}$, which is clearly lower than the detection given by Womack and Stern in June. However, averaging measurements over such a large time range neglects possible long-term trends in activity.

The production rate upper limits for Chiron are based on models derived for *conventional* comets, or on the assumption of parameters measured in comet 29P/Schwassmann-Wachmann 1, which, however, may not be valid for Chiron because of the large size of this object. For instance, part of the dust coma may be semi-captive because of gravity, and expansion cooling of gas may not be so efficient because of the large size of the nucleus. According to the model of the dusty coma of Chiron by Boice et al. (1993) and Boice and Benkhoff (1996), gas-dust collisions allow the gas temperature to equilibrate with dust. The gas coma of Chiron may thus be warmer than in other distant comets. With $T_{rot}$ much larger than 10 K (the value assumed in our analysis, similar to the range assumed by Womack and Stern of 10 - 50 K), our limits on the gas production rates would not be so stringent.

In addition to CO, we searched for other molecules more volatile than water in the coma of Chiron in November 1995 and January 1996. For CN we derive a $3\sigma$–upper limit of $8.4 \times 10^{25}$ $s^{-1}$. This is in the same range as the value derived by Bus et al. (1991) in 1990 ($3.7 \times 10^{25}$ $s^{-1}$) using a vectorial model. Assuming all CN comes from HCN, the upper limits on the production rates derived from the optical are in agreement with the direct upper limit on the HCN production rate derived from radio observations.

Although an extrapolation of abundance ratios from 1 AU to large heliocentric distances is not strictly allowed, we briefly discuss the ratios expected for comparison with our upper limits. The abundance ratio of HCN to CO in 'normal' comets at around 1 AU is about 0.02. Assuming the CO production rate of Chiron to be equal to the upper limit in November 1995 ($2\times10^{28}$ s$^{-1}$) we would expect the HCN production rate to be higher than our upper limit on HCN. The same holds for $H_2CO$, whereas our upper limit on $H_2S$ seems to be meaningless. Thus, the derived upper limits imply either a reduced production of HCN and $H_2CO$ (if we believe the assumed value for the CO production rate), or that the CO production rate must have been significantly below the upper limits derived here. However, extrapolating from 1 AU assumes that the abundance ratios remain constant with varying heliocentric distance. This might not be the case, especially at large heliocentric distances where the surface temperature can drop below the sublimation temperature for some of the observed species. However, measurements and models of Chiron's surface temperature (see Prialnik et al., 1995, and references therein) show that its surface temperature could be above 120 K, even at 10 AU. This is sufficient for HCN ice to sublimate. On the other hand, little is known about the exact sublimation mechanism at such large heliocentric distances and its effect on the abundance ratio of molecules with very different sublimation temperatures. Observations of comet Hale-Bopp at 6 AU indeed showed a much lower ratio of Q(HCN)/Q(CO), less than 0.005 (Biver et al., 1996). Unfortunately, from our available data on Chiron (only upper limits) we cannot firmly conclude on the relative outgassing of the species observed.

Dust injection rates in Chiron's atmosphere are modest: 1–4 kg s$^{-1}$ according to Luu and Jewitt (1990) and Meech and Belton (1990). This is to be compared with our limit on CO which amounts to about 500 kg s$^{-1}$. Recent observations of comet C/1995 O1 (Hale-Bopp) have shown that a huge dust production can be sustained by a more modest gas production (Biver et al. 1996). Indeed, our measurements poorly constrain the gas-to-dust ratio in Chiron's atmosphere.

The normalized reflectivity gradient found in Chiron in January 1996 corresponds to a neutral colour in the range from 4000–4775 Å and a slightly red colour from 3600–4000 Å. To compare this with previous measurements, we also computed the gradient from 3700-4600 Å. The resulting gradient of 2.4±0.1 %/$10^3$ Å is in the range of values previously measured. Luu and Jewitt (1990) report a gradient of 1.6±0.5 %/$10^3$ Å for February 1989 and of 5.1±0.5 %/$10^3$ Å in February 1990. However, during observations in 1991 and 1992, a blue colour of Chiron was found (Luu, 1993). The causes for the slight differences in colour seen in the various observations remain presently unclear.

Our upper limits derived from optical and millimetre observations showed that Chiron's level of activity did not increase significantly when approaching perihelion. Although the solar flux increased by a factor of 2 between the measurements taken by Bus et al. (1991) at 11.3 AU, which resulted in the detection of CN, and the measurements presented here, no CN emission could be found in our data. Thus, Chiron's activity does not seem to vary strongly with decreasing heliocentric distance. This observation might help constraining activity models. In the model of Prialnik et al. (1995), Chiron's nucleus was assumed to contain amorphous water ice loaded with trapped dust, CO and $CO_2$ (but no CO or $CO_2$ ice). Their modelling of the evolution of Chiron's activity predicted production rates of CO in the range $10^{26}$–$10^{27}$ s$^{-1}$, which is lower than our observed limits by more than one order of magnitude. It is interesting to note that this model predicts a slight decrease in CO production as the comet approaches perihelion, contrary to the usually assumed increase proportional to $r_h^2$ for comets close to the sun.

## 6 Conclusion

2060 Chiron reached its perihelion on 14 February, 1996. It was expected that an increased level of activity could be observed with decreasing heliocentric distance. A 300 s exposure of Chiron taken on 26 January, 1996, through a V filter with the 2.2m telescope at ESO, Chile, indeed showed a faint tail extending along the antisolar direction. The reflectivity gradient derived from optical spectra taken from 25-28 January, 1996, is in the range found in previous observations.

To investigate the nature of outgassing at large heliocentric distances, we searched for radio emission lines of CO, HCN, $H_2S$ and $H_2CO$ from June to November 1995 with the IRAM 30-m telescope. The optical spectra taken at ESO during January 1996 were used to search for emission of CN (a daughter of HCN). No gaseous emission features could be detected in our observations. We do not confirm the claimed detection of CO. A CN emission, as observed during the 1990 outburst, is not found in the present observations. The spectra have been used to derive upper limits on the gas production rates (Tables 2 and 3).

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**Table 1: Observations of 2060 Chiron at optical and millimetric wavelengths:**

| **date** | **r**$_h$ [AU] | **Δ** [AU] | **searched species** | **frequencies or wavelength** | **integr. time** [min] |
|---|---|---|---|---|---|
| 23-26.6.1995 | 8.50 | 8.65 | CO(2-1) | 230 GHz | 335 |
| | | | CO(1-0) | 115 GHz | 335 |
| 20/21.9.1995 | 8.47 | 9.47 | CO(2-1) | 230 GHz | 115 |
| | | | CO(1-0) | 115 GHz | 115 |
| 13-20.11.1995 | 8.46 | 9.13 | CO(2-1) | 230 GHz | 444 |
| | | | CO(1-0) | 115 GHz | 48 |
| | | | HCN(1-0) | 89 GHz | 360 |
| | | | $H_2S(1_{10}$-$1_{01})$ | 168 GHz | 222 |
| | | | $H_2CO(2_{12}$-$1_{11})$ | 141 GHz | 144 |
| 25-28.1.1996 | 8.45 | 8.04 | CN 3875 Å | 3550-4550 Å | 255 |

**Table 2: Search for CO emission lines:**

| **date** | **r**$_h$ | **Δ** | **CO(1-0)** | | **CO(2-1)** | |
|---|---|---|---|---|---|---|
| | | | $\int \mathbf{T_b dv}^*$ | **Q** | $\int \mathbf{T_b dv}$ | **Q** |
| | [AU] | [AU] | [K km s$^{-1}$] | [s$^{-1}$] | [K km s$^{-1}$] | [s$^{-1}$] |
| 23-26.6.1995 | 8.50 | 8.65 | <0.054 | $<5.6\ 10^{28}$ | <0.063 | $<2.0\times10^{28}$ |
| 20-21.9.1995 | 8.47 | 9.47 | <0.072 | $<8.1\ 10^{28}$ | <0.068 | $<2.3\times10^{28}$ |
| 13-20.11.1995 | 8.46 | 9.13 | <0.091 | $<9.9\ 10^{28}$ | <0.043 | $<1.6\times10^{28}$ |
| all | 8.48 | 9.02 | <0.043 | $<4.6\ 10^{28}$ | <0.030 | $<1.0\times10^{28}$ |

*: $3\sigma$ upper limits computed from -0.6 km s$^{-1}$ to 0.6 km s$^{-1}$

**Table 3: Search for other volatiles:**

| **molecule** | **date** | $\mathbf{r}_h$ [AU] | $\Delta$ [AU] | $\int \mathbf{T}_b\ \mathbf{dv}^*$ [K km s$^{-1}$] | **flux** [erg cm$^{-2}$ s$^{-1}$] | **Q** [s$^{-1}$] |
|---|---|---|---|---|---|---|
| HCN | 13-20.11.1995 | 8.46 | 9.13 | $<$0.022 | – | $<1.3\times10^{26}$ |
| $H_2CO$ | 13-20.11.1995 | 8.46 | 9.13 | $<$0.029 | – | $<4.2\times10^{26}$ |
| $H_2S$ | 13-20.11.1995 | 8.46 | 9.13 | $<$0.060 | – | $<2.1\times10^{27}$ |
| CN | 25-28.1.1996 | 8.45 | 8.04 | — | $<5.6\ 10^{-16}$ | $<8.4\times10^{25}$ |

*: $3\sigma$ upper limits computed from -0.6 km s$^{-1}$ to 0.6 km s$^{-1}$ for radio observations; CN line width used: 9 Å, taken from Bus et al., 1991.

**Table 4: Normalized reflectivity gradient:**

| **wavelength range** | **norm reflec. gradient** |
|---|---|
| 3600 - 4000 Å | 12.3 % /$10^3$Å |
| 4000 - 4775 Å | 0.2 % /$10^3$Å |
| 3700 - 4600 Å | 2.4 % /$10^3$Å |

**Figure captions:**

**Figure 1:** 2060 Chiron on 26 January, 1996, at 06:04 UT, observed in a V filter (exposure time 300 s). The field shown covers 2.8×2.8 arcmin. North is to the top, east to the right. A faint dust tail extending along the anti-solar direction is seen (position angle: 294°).

**Figure 2:** Normalized reflectivity gradient of 2060 Chiron obtained on 25-28 January 1996.