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The Activity of Comet 29P/Schwassmann-Wachmann 1 Monitored Through the CO J(2–1) Emission Line at 230 GHz

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CO J(2–1) emission from comet 29P/Schwassmann-Wachmann 1 at 230 GHz was observed on 16 occasions with the 15-m SEST antenna from 4 December 1996 until 2 January 1997. A clear signal was detected in all daily averaged spectra, and day-to-day nuclear output variations by a factor ~ 2 were observed. Whatever the position of the telescope main beam in the coma, the line position and shape showed remarkably stable characteristics, which justified to combine the spectra to produce line profiles with S/N greatly enhanced over previous observations of the same kind. While most of the outgassing occurs from the sunlit side of the nucleus, night-side emission is also present. The shape of the lines near zero velocities in offset spectra cannot yet be uniquely interpreted. Whatever the ultimate model proposed to explain these observations, important implications for our understanding of how CO molecules are stored in the nucleus and later released into the coma may be derived from this data set.

Comet 29P/Schwassmann-Wachmann 1 (hereafter designated as SW1) was long the only object of proven cometary nature found to orbit the Sun entirely outside the orbit of Jupiter, at an average distance of ~ 6 AU. Rickman speculated in 1985 that Chiron, an object of apparently cometary nature and giant size, only physically observable with large-size telescopes, could be one of the largest members of an unseen population of comets orbiting the Sun between the orbits of Jupiter and Neptune[1]. In recent years, an ever-growing number of solar-system objects have been discovered that are also constantly situated far from the Sun. They form the now called Centaur and Kuiper Belt (KB) families, two groups of bodies that circulate between the orbits of Jupiter and Neptune and on average beyond that of Neptune, respectively. From a dynamical point of view, the Centaurs may be escapees from the Kuiper Belt. While the true nature of these newly discovered objects still remains to be unveiled, the current thinking is that they are the largest members of a vast reservoir of potential comets proposed by Fernandez[2] in 1980 to provide an important additional source of short-period comets beside the Oort cloud. The Centaur and KB populations should contain numerous small comets that are not observable with today's instruments. It is currently impossible to state whether SW1 was captured from the Oort cloud or the KB. In the light of all these new developments on the origin and evolution of orbits of comets, SW1 undoubtedly is a unique object that deserves attention besides the interest it has always aroused for its peculiar brightness behaviour.

SW1 is known since its discovery in 1927 for its numerous and unpredictable bursts of activity, some of which bring its magnitude down to 10–11 from a state of much lower brightness long

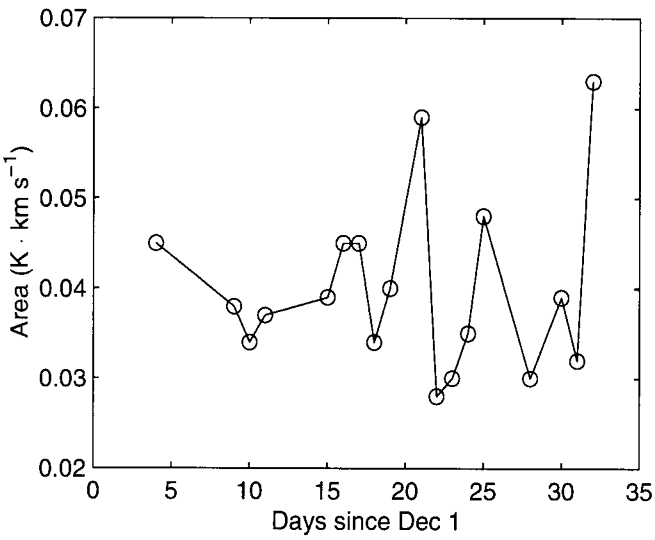

Figure 1: CO production in comet SW1 measured during the month of December 1996. The comet was observed during a period we can qualify, based on the comet total magnitude, as of "low" or "minimal" activity, the so-called "quiescent state".

thought[5] as being a “dormant state”. The comet would be inactive most of the time and would become suddenly, say every two months or so, much brighter, the indisputable proof that its nucleus is active. A dust coma would then form, driven by an unseen gas. Spectroscopic observations of comets indicate that water is the most abundant volatile species in their nuclei, and laboratory data further indicate that water should not sublimate at distances from the Sun larger than 4–5 AU. However, it is not uncommon for comets observed at distances from the Sun larger than this limit, both on the incoming and outgoing branches of their orbits, to display a well-developed dust coma. C/Hale-Bopp (1995 O1) is the most recent example – and how famous! – of an object moving towards the Sun from remote neighbourhoods, that has consequently not been heated since long, and that displays activity when water cannot escape its nucleus[3, 4]. A question of paramount importance is thus “what is the nature of the outgassing agent that controls the activity of distant comets and how can this gas leave the nucleus?”. One would normally expect a dust mantle and/or water ices to block the way towards the surface. One can see now the key role played by comet SW1, possibly a pristine and relatively unevolved object. Like all objects never coming closer to the Sun than $\sim$ 5 AU, its nucleus is subject to only mild heating, and its surface temperature never goes beyond that of the water sublimation threshold.

In 1987–88, a large set of CCD images of comet SW1 was obtained by Jewitt[5], which showed that the comet was permanently active and always surrounded by a dust coma, even when its magnitude was near a maximum value of R $\sim$ 16.5 (maximum magnitudes previously derived from photographic plates[5] – nearly equivalent to B magnitudes – are of order 18–19 and underestimate the true comet brightness by $\sim$ one unit[6]). The nature of the outgassing agent in SW1 is known since 1994, when CO was detected for the first time

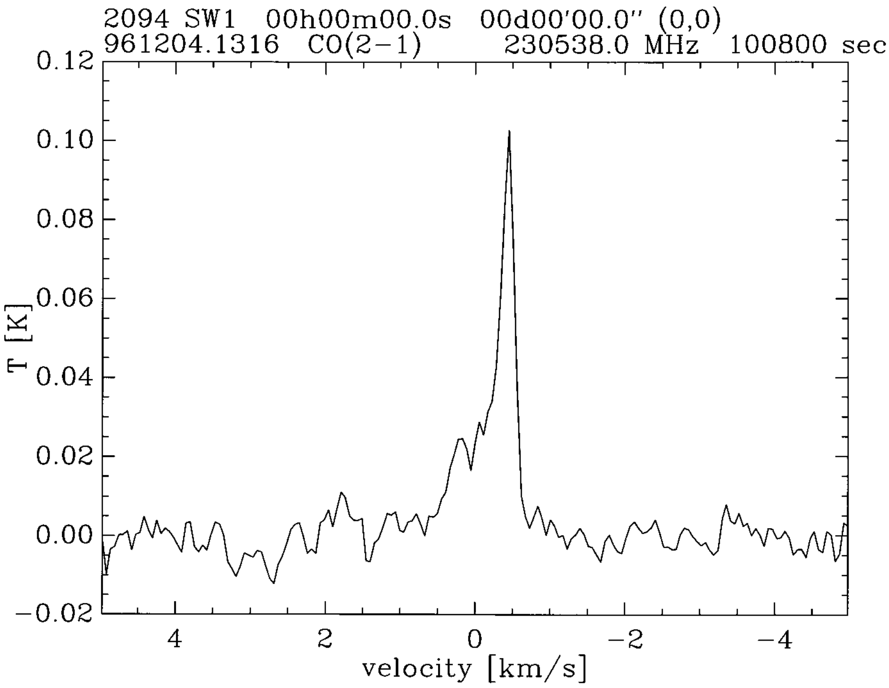

Figure 2: Average ON spectrum in December 1996. The time spent with the source in the aperture is 50,400 sec. The line peak position indicates a sunward ejection of matter at a velocity of order 500 m s^{-1}. The width of the peak is a measure of the kinetic temperature of the gas, $\sim$ 12 K.

by Senay and Jewitt[7] from the JCMT by its emission at 230 GHz, based on a prediction made by Crovisier a year earlier[8]. The Meudon cometary team confirmed this important observation a little later[9]. These two data sets reveal that the CO line is very narrow and blue-shifted by $\sim$ 0.4 km s^{-1}. An isotropically emissive coma would produce a line centred on the zero velocity, and the observed line displacement indicates an ejection of matter on the sunward side of the nucleus. The sharpness of the main peak of the line is the result of both an undersampling of the coma by the telescope main beam and a low kinetic temperature. The gas flows from the nucleus at a fairly high nearly monokinetic velocity, 300–500 m/s from the early measurements, and molecular collisions taking place near the nucleus do not widen the peak thus formed. Due to the long lifetime of the first CO rotational levels ($\sim 10^6$ s) and the slow rate of pumping in the IR vibrational 1–0 lines, the rotational temperature acquired in the inner coma is conserved through most of the coma. These phenomena have typical scale lengths of the order of, or larger than, 10^5 km and we evaluate the effect of IR pumping to be 10% or less over the entire SEST antenna telescope main beam. The higher resolution IRAM data further showed the existence of a “skirt” extending to red-shifted velocities, a feature that was readily interpreted as proof of night-side outgassing. The present programme, conducted with the SEST 15-m diameter antenna, was designed to extend the previous observations over a significantly longer period of time and to determine what the normal “gaseous” state of activity of the comet was. Our main objectives were to measure the CO production on a daily basis for about 30 days, fully define the CO line parameters (width and line position), establish the reality of a night-side outgassing and, if possible, observe an outburst in progress.

Monitoring of the CO J(2-1) line began on 4 December 1996 and ended on 2 January 1997 and data were collected on 16 different days. The average time spent with the source in the telescope beam was of the order of 90 minutes per day. The comet was detected in all daily averaged spectra at a level of 0.04–0.08 K km s^{-1} with a S/N intermediate between that obtained with the JCM and IRAM antennae. It was found that the day-to-day variability of its CO production rate was about 2 (Figure 1 shows the production curve derived from our daily averaged “ON” spectra, assuming a nuclear source of CO, details on the model we used are given below). CCD images taken with the 1-m telescope of the DENIS project at the end of December 1996 on 3 consecutive nights showed a changing coma whose V magnitude was $\gtrsim$ 16. The line, as found in previous observations, was composed of a narrow and strong peak of FWHM $\sim$ 0.1 km s^{-1} blue-shifted by $\sim$ 0.45 km s^{-1}. On closer inspection, it appeared that the line profile extended towards negative radial velocities (the “skirt”). This is well seen in the average “ON” spectrum shown in Figure 2. There was no indication, within our noise level, that the line position changed with either time or activity. The CO velocity did not vary despite a nuclear activity level that was observed to change from one day to the next by a factor $\sim$ 2. We also note that past observations of comet SW1 did not reveal any changes in the velocity of the dust (always found to be $\sim$ 150 m s^{-1}), even when the nuclear activity level changed by a large factor. More recently, distant radio observations of C/Hale-Bopp, an indisputably very active comet, never revealed the presence of high gas velocities, despite the extremely large CO production measured in that comet. All this leads to the idea that the line displacement and width take values directly related to the process whereby the gases leave the nucleus but not so much to the amount of material thus produced. (Of course, near the sun, photolytic heating is a source of energy that may efficiently increase the velocity of coma species).

A study of the spatial distribution of CO molecules around the nucleus of the comet is in progress. The main spectral features, namely the peak position and width, are explained if outgassing occurs mainly on the sun-side and if its local rate is proportional to the square of the insolation and if the outflow velocity is proportional to that insolation. Since the outflow velocity is expected to vary as the surface temperature, this indicates that conduction must play a major role in controlling the surface temperature. The narrowness of the main peak is due to the low kinetic temperature of the gas. The presence of CO molecules with near-zero and negative velocities requires introducing some night-side outgassing. The assumption of LTE for the excitation holds because the rotational relaxation time constant and IR pumping rates are rather large, of the order of a few 10^5 sec and a few 10^{-6} sec. respectively. If the telescope main beam were larger, the line shape would be quite different (the theoretical line profile for an isotropic outflow from a point source observed through a telescope main beam of large size compared to that of the coma is a rectangle of full width twice the outflow velocity), and more molecules would be observed with zero projected velocities. In our modelling, we adjust the night-side velocity to match the data and we derive that the CO flux on the night-side is ~ 15% of that at the sub-solar point.

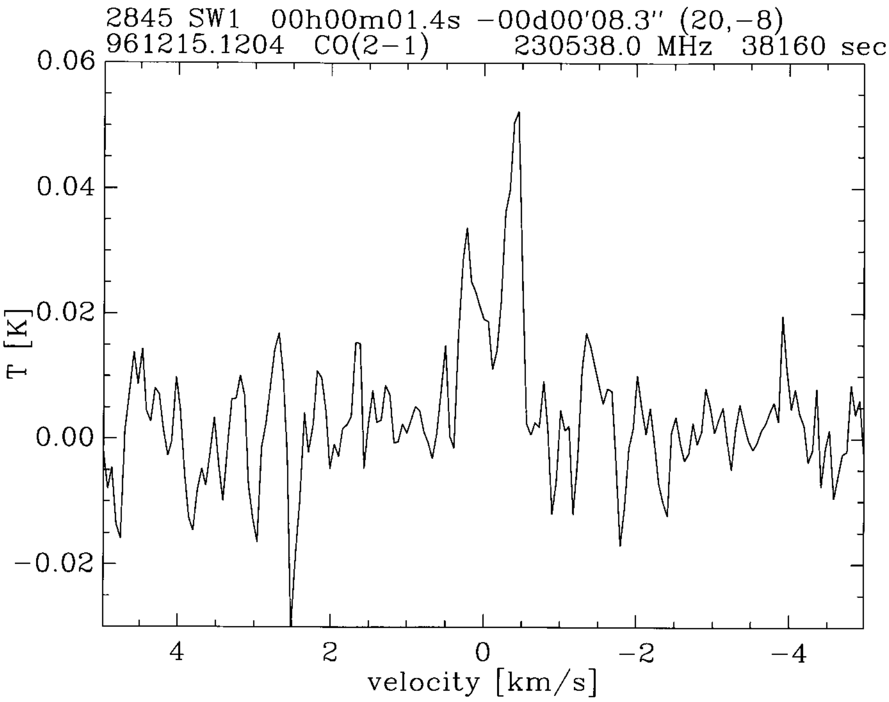

Figure 3: Mean line shape recorded in December 1996 when the telescope main beam was put 22 arcseconds away from the nucleus, sunward. The decrease in line area, within the pointing uncertainties, is barely compatible with a source of CO at the nucleus and this could be the indication of the presence of a second component produced in an extended region.

Complementary integrations were made at three offset positions inside the coma, at 11 arcsec anti-sunward, 11 and 22 arcsec sunward, respectively. Our ON and 22 arcsec sunward spectra are shown in Figures 2 and 3, respectively. It readily appears that the peak seen in the ON integration is also present in the offset integration, at the same velocity of ~ 400 m s^{-1}. This was to be expected given the observing geometry: both the Sun and the Earth are on the same side of the nucleus and the Sun-comet-Earth angle is only 9 degrees. More surprising is the structure seen near zero velocity values. Since the telescope main beam is undersampling the CO cloud, the magnitude of this structure implies a large population of CO molecules with small radial velocities. Its presence either implies a massive injection of CO molecules in a very specific direction, near the Sun-Earth-comet plane and away from the Earth (i.e. near the terminator) or the existence of CO molecules on the sunward side that barely move. Time resolved observations of the activity of comets (e.g. comet Levy, Feldman et al.[10] or comet Hale-Bopp, Bockelée-Morvan et al.[11]) have shown that the nucleus responds rapidly to any change in the insolation pattern of the nucleus and the presence of a second component at a fixed velocity during all our observations could mean that the rotation axis of SW1 was not too far from the sunward direction. This hypothesis seems somewhat *ad hoc* at the present time and additional observations are required to confirm or reject it. Another possible explanation is to suppose that some CO radicals are produced from grains that move very slowly on the sunward side. We are currently investigating this hypothesis, although there are difficulties associated with it too. One expects the gas to be able to entrain fairly large grains, and either those grains would evaporate rapidly to allow for the molecules to be excited in the collisional part of the coma or we have underestimated the role of the extended source of CO and that of the associated IR excitation mechanism.

The mean gaseous output of the comet is ~ 1 ton per second, i.e. similar to the dust production rate derived from optical images by Fulle[12]. At that rate, comet SW1 can be continuously active for 10^4 revolutions, or a time much larger than its dynamical lifetime.

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