Reports

Detection of CN Emission from (2060) Chiron

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In the past decade there has been a gradual, but substantial change in our understanding of the physical nature of (2060) Chiron. Once thought to be the first known member of a population of asteroids orbiting between Saturn and Uranus, Chiron is now generally regarded as the largest known comet. The detection of CN emission in the spectrum of Chiron is reported. Not only do these observations underscore the cometary nature of Chiron, but, at a heliocentric distance exceeding 11 astronomical units, represent the most distant detection yet of a neutral gas species common in comets. These results are consistent with the outgassing from Chiron being primarily driven by isolated outbursts of CO_2 from a very small fraction of Chiron's surface. These may be indicative of primordial inhomogeneities.

THE UNUSUAL NATURE OF (2060) Chiron has become increasingly apparent since Kowal's discovery of the object in 1977 (*1*). In spite of Chiron's large heliocentric distance and unstable orbit (*2*), the first physical observations supported its classification as an asteroid (*3*). However, in early 1988, Chiron was observed to brighten more rapidly than predicted for an inert body approaching perihelion (*4*). Although cometary activity was suggested, the cause of this "non-asteroidal" brightening remained uncertain until 1989, when a faint dust coma around Chiron was first imaged (*5*). Subsequent work has confirmed the existence and overall appearance of the dust coma (*6, 7*) and has led Hartmann *et al.* (*8*) to suggest that Chiron may undergo sporadic, cometary outbursts similar to those seen in comet P/Schwassmann-Wachmann 1. Just such an outburst was later observed by Luu and Jewitt (*7*). Spectroscopic observations of Chiron have been made by some observers (*7, 9*) since the onset of comet-like behavior, but no detection of gaseous emission bands has been reported. Stern (*10*) has shown that, if present, specific volatiles on Chiron could be used to place limits on this object's residence time in the planetary region of the solar system.

We present spectrophotometric observations of Chiron made on 30 January 1990 UT, when the object was at a heliocentric distance of 11.26 AU and a solar phase angle of 2.4°. These observations were obtained with the Ohio State University CCD Spectrograph on the 1.8-m Perkins reflector of the Ohio Wesleyan and Ohio State Universities at Lowell Observatory. The spectrograph, which houses an ultraviolet-enhanced TI-4849 390 by 584 pixel CCD, was oriented with the slit in the east-west direction, and the slit width was set to 1.5 arc sec. The spatial scale of the CCD was 0.75 arc sec per pixel and the wavelength scale was 4.555 Å per pixel, yielding an effective spectral resolution of about 10 Å. To eliminate nonlinear response at very low light levels, the CCD was preflashed for 20 ms prior to each exposure. Seven 20-min integrations were taken of Chiron in the spectral region from 3300 Å to 5800 Å on 30 January between 7:00 and 10:30 UT. In addition, multiple bias and flat-field frames were obtained, as well as frames of FeNe comparison lines for wavelength calibration, of HD84937 for flux calibration, and of HD28099 (vB64) as a solar analog for continuum subtraction.

Bias was removed from the images by first subtracting a uniform value determined within an overscan region in each image, and then subtracting a full-field "residual" frame which primarily contains structure resulting from the preflash process. We made the responsivity uniform across the CCD using flat-field images taken of a diffused quartz lamp source located in the spectrograph. Isolated pixels that had abnormally high values, usually due to cosmic ray hits, were identified and replaced by fits to surrounding pixels. After wavelength calibration and correction for atmospheric extinction, for which we used mean coefficients, each image of Chiron was flux-calibrated using the extracted measurements of HD84937. However, because the spectrograph slit was not widened to accommodate the entire stellar image, a significant fraction of the light from the flux standard was not admitted. By examining the star's profile along the slit, we estimated that only 20% (±4%) of the flux was accounted for in the extracted spectrum of HD84937. The error in this estimate contributes to much of the uncertainty in the absolute flux calibration of any extended features in Chiron's spectrum. The final calibrated images were then registered and added, producing a single image with a total integration time of 140 min. We looked for evidence of faint extended emission from the object, but saw nothing between 15 and 100 arc sec on either side of the photocenter. Likewise, we could not detect the dust coma in these regions, which is consistent with the surface magnitude of B = 26 mag arc sec^{-2} at a 15-arc sec radius (*6*). Therefore, we carried out sky subtraction using a second-degree polynomial fit made to each row of pixels 30 to 60 arc sec on each side of Chiron. As is often the case, this procedure did not fully remove all sky features, but resulted in faint remnants of night sky emission lines in the sky-subtracted image.

Apparent in the final summed image, both before and after sky subtraction, is the CN (0-0) band centered at 3875 Å (Fig. 1). This is precisely the wavelength of the narrow CN band expected from fluorescence at a heliocentric distance of 11 AU as determined from calculations made with the procedures described by Schleicher (*11*). The band extends symmetrically on both sides of the continuum spectrum out to at least 7 arc sec, or about 50,000 km at the distance of Chiron. The feature cannot be detected in any of the individual images, but it becomes visible when any combination of three or four of the images are co-added, thus ruling out the possibility that abnormally high pixels in any one image are dominating the results.

We extracted two one-dimensional spectra from the final image of Chiron: one with an aperture 19.5 arc sec wide centered on Chiron (Fig. 2A), the other with a double aperture, each component of which extended from 1.5 to 6.0 arc sec on opposite sides of Chiron's photocenter (Fig. 2B). In both cases we scaled the spectrum of the solar analog, HD28099 (vB64), to Chiron's spectrum over the region from 3600 Å to 4500 Å using a third-degree Chebyshev polynomial fit, and then subtracted the fitted solar analog spectrum from that of Chiron. In Fig. 2B, the flux in CN is 7.3×10^{-16} erg cm^{-2} s^{-1}, while the root-mean-square (rms) pixel-to-pixel variation is 2.2×10^{-17} erg cm^{-2} s^{-1} Å^{-1} or 1.0×10^{-16} erg cm^{-2} s^{-1} pixel^{-1}. Because the CN flux is contained

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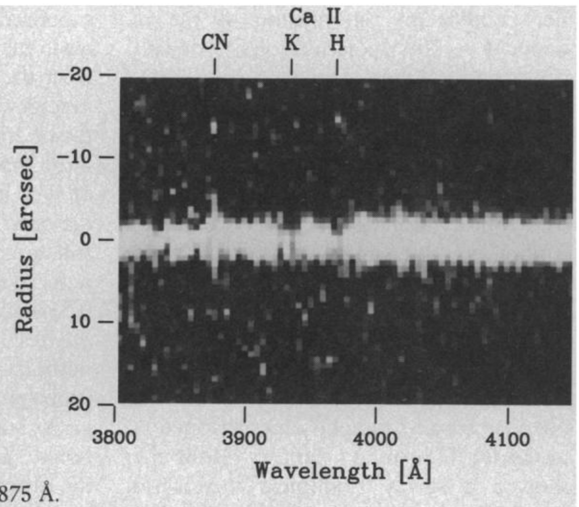

Fig. 1. A portion of the two-dimensional spectral image of Chiron resulting from the average of seven individually reduced exposures from which Chiron's reflected solar continuum has not been subtracted. The spatial scale along the slit is 0.75 arc sec per pixel, and the dispersion is 4.555 Å per pixel. A 3 by 1 pixel smoothing function, equivalent in extent to the characteristic seeing of 2 arc sec and weighted in the form [0.25, 0.50, 0.25], has been applied to the image in the direction parallel to the slit, reducing the apparent level of background noise while not affecting the spectral resolution. Visible are the CaII H and K absorption lines in the solar continuum, and the extended CN (0-0) band centered at 3875 Å.

within two pixels of the rebinned spectrum, the resulting rms error is $\pm 1.4 \times 10^{-16}$ erg cm^{-2} s^{-1}, yielding a 5σ detection for CN. Combining this measured photometric uncertainty with the aforementioned estimated error in absolute flux calibration yields a net flux due to CN of $(7 \pm 2) \times 10^{-16}$ erg cm^{-2} s^{-1}. The spectrum in Fig. 2A has additional noise from the strong continuum, and includes pixels where CN is very weak, yielding less than a 4 σ detection, with an integrated CN flux of $(8.5 \pm 3) \times 10^{-16}$ erg cm^{-2} s^{-1}.

We created a radial profile of the CN emission along the slit (Fig. 3) by extracting three columns of pixels from the original image (Fig. 1) centered on the CN feature. We also constructed a continuum profile along the slit by combining columns from Chiron's image over the wavelength region 4100 to 4320 Å, and scaling to the continuum level at CN using flux measurements from the solar analog. Subtracting the continuum profile from that of CN gives an indication of the distribution of CN along the slit. There is a 2-pixel-wide gap in the CN profile, very near the photocenter of Chiron. We made several attempts to rescale the continuum profile using different measurements of the solar analog, but the results were similar. Given the level of noise elsewhere along the CN profile, we cannot attach much significance to the gap, even though such a feature is what one would expect if the gas were distributed as a shell of material around Chiron. Using this profile, we calculated the CN flux as $(7 \pm 3) \times 10^{-16}$ erg cm^{-2} s^{-1}, consistent with the above estimates.

In order to interpret the observed CN in terms of simple models for the outflow of gas, it is most convenient to consider a circular field of view and determine the total number of CN radicals in that field. Because the emission feature extends roughly equally on both sides of the nucleus and because Chiron was nearly at opposition at the time of the observations, we assumed that the true spatial distribution is circularly symmetric. We will assume a simple trapezoidal spatial profile, as shown in Fig. 3, which has uniform surface brightness of 3.1×10^{-17} erg cm^{-2} s^{-1} arc sec^{-2} (~3 Rayleighs) to a radial distance of 5 arc sec and which declines linearly to zero at a distance of 10 arc sec. This profile reproduces the total flux in the spectrograph slit obtained by numerically integrating the noisy, observed profile. Integrating the trapezoidal profile over a circle of radius 10 arc sec yields a total flux of 5.7×10^{-15} erg cm^{-2} s^{-1}. Using the fluorescence efficiency of CN at 11 AU, a by product of the calculation which produced the spectral profile of Fig. 2C, we find that the total number of CN radicals in the circular field of radius 10 arc sec is 5.3×10^{29}.

We think that the unknown parent of CN is being carried along by outgassing driven by sublimation of either CO or CO_2 ice. It is known that HCN was present in P/Halley (*12*) and that it is presumably one of several parents of CN in that comet. The best estimates of its abundance, however, were too low for HCN to be the sole parent of the observed amount of CN. Another source of CN in P/Halley is thought to be direct release from the distributed grains in the coma, probably grains of CN-bearing polymers (*13*). In the case of Chiron we have no a priori method of determining the parent of

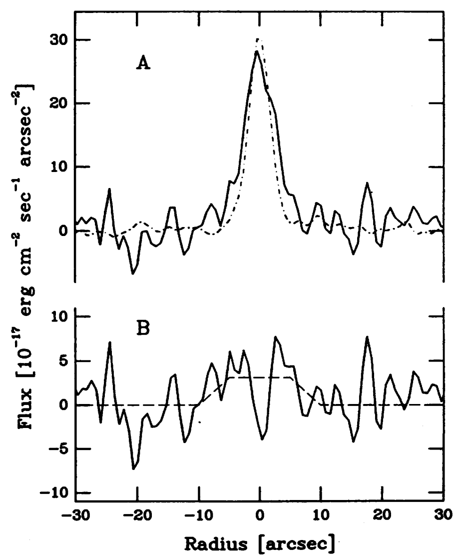

Fig. 3. (**A**) Spatial profile of flux (solid curve) along the slit, created by collapsing down the three columns of pixels that contain the majority of the CN flux. A continuum profile (broken curve) was likewise created by collapsing 50 columns from Chiron's image over the wavelength region 4100 to 4320 Å, and by scaling flux measurements from the solar analog HD28099. (**B**) The difference (solid curve) between the two profiles shown in (A), giving the actual CN flux distribution along the slit as a function of distance from Chiron. The dashed curve represents the trapezoidal model distribution of CN used in our modeling.

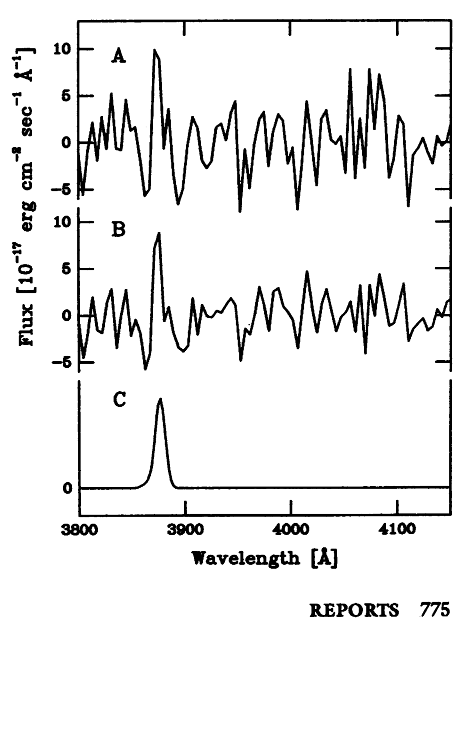

Fig. 2. Curves (**A**) and (**B**) show flux-calibrated spectra of Chiron that have the same wavelength coverage as in Fig. 1, but from which the fitted solar continuum has been subtracted. In comparison to the image in Fig. 1, it should be noted that during the extraction of these one-dimensional spectra, the data were rebinned to a dispersion of 4.50 Å per pixel. Spectrum (A) represents the total signal within a 19.5-arc-sec-wide aperture perpendicular to dispersion and centered on Chiron's photocenter. To reduce the level of noise, spectrum (B) includes only the signal within the pair of apertures extending from 1.5 to 6.0 arc sec on opposite sides of Chiron's photocenter, where the flux from CN emission is strongest. Spectrum (**C**) is a model band profile (arbitrarily scaled) for CN emission, in air, based on fluorescence equilibrium calculations for CN at a heliocentric distance of 11 AU using procedures described by Schleicher (*11*), and convolved to the appropriate spectral resolution. Notice the strong similarity in both the band location and width compared to the observed spectrum of Chiron.

CN, but the numerical parameters for modeling the outflow and distribution of CN are available for HCN whereas they are not available for the CN-bearing polymers. For discussion of a model, therefore, we will temporarily assume that the parent of CN is HCN. This species has a lifetime in sunlight of 6.6×10^4 s (at 1 AU from the sun, scaling as r^{-2}) and on dissociation the CN radical receives an excess velocity of 1.2 km s^{-1} (*14*).

The presence of CN can be interpreted in two ways: either as the result of continuous outgassing or as the result of a recent outburst. Since both phenomena are known to occur in comets closer to the sun and since there are no relevant observations of other comets at Chiron's heliocentric distance, there is again no obvious, a priori choice between the two cases. We will therefore consider both interpretations.

We carried out numerical calculations to simulate the steady-state flow using code described and developed by Festou (*15*). According to these calculations a steady-state outgassing of 3.7×10^{25} HCN molecules per second would explain our observed CN. If the source of the CN is the grains, the problem is much more complicated. If the grains are very small so that they are entrained by the gas and can escape Chiron's gravity, the model is similar but the outflow velocity is smaller (by an unknown amount) and the excess velocity on dissociation is likely also smaller. Thus a smaller production rate of "parent molecules" can explain the same observed abundance of CN. If the grains are somewhat larger, they form a bound atmosphere as discussed by Meech and Belton (*16*) and the release depends on the lifetime of the grains against depletion of CN radicals from surface sites. Because the numerical parameters for such a model are not known, any calculation would be purely speculative but such a model is certainly plausible and capable of explaining the observations.

To explain the required rate of outgassing of CN, we will assume that the driving force is sublimation of either CO or CO_2. We assume that the surface is dark, having 10% reflectivity, which is consistent with the limited results available for Chiron (*4, 17*) but somewhat brighter than is typical of other cometary nuclei (*18*). For purposes of discussion we assume that the dirty ice is subliming in equilibrium with the incident sunlight on the basis of the formalism described by many authors including ourselves (*19*). We assume that the CO or CO_2 is ten times more abundant than the CN, consistent with the measured CO_2 production in P/Halley (*20, 21*) and within the range (0 to 7% relative to water) for the direct nuclear source of CO determined in P/Halley (*22*).

For equilibrium vaporization of the required 4×10^{26} molecules of CO or CO_2 per second, we then require a surface area of 0.6 or 3.8 km^2, respectively. This is only a tiny fraction of the total surface area of Chiron (*4, 17*). Alternatively, the ice might be distributed more widely but somewhat below the surface. Although the scenario of continuous outgassing is quite plausible, we think for other reasons that it is not the correct one.

The existence of an outburst of dust precisely at the time of our observation is clear from results by Luu and Jewitt (*7*), who obtained broad-band photometry from 6:00 to 14:00 UT on 29 January 1990 that showed a steady brightness increase of 0.015 magnitude per hour with a modulation attributable to rotation of the nucleus superimposed. Additional observations near 6:00 UT on 30 January, only 90 minutes prior to the start of our observations, showed that the brightness was about the same as at the end of the series of observations on 29 January. Determining the time of onset of this outburst, however, is more difficult because there are no data on preceding nights. We must therefore set some limits by considering earlier photometry to estimate the magnitude before the outburst.

We have combined the photometry from 1989 by Meech and Belton [(*16*); reduced to absolute *R* magnitudes, H_R] with the photometry from 1989 by Luu and Jewitt (*7*) to describe the gradual decline of Chiron's brightness from its peak in late 1988. Because the data are sparse, extrapolation to 29 January 1990 is rather uncertain, but in our opinion any extrapolation of the lower envelope of the points (points above the lower envelope are presumably affected by earlier outbursts) implies that the outburst began with H_R brighter than 5.8 mag. This in turn requires that the outburst began within an hour or two before the start of Luu and Jewitt's observations on 29 January. An even more extreme estimate can be made by considering the typical magnitudes of Chiron in 1987–1988, which averaged about $H_R = 6.25$ [see figure 1 of (*7*)]. Even this extreme would imply that the outburst began only 30 hours before the observations started on 29 January but we think this latter situation is quite unlikely.

Empirically, we find that the emission by CN extends to approximately 10 arc sec or 75,000 km from the nucleus. In most cometary situations this would correspond to the rather arbitrary point at which the gradually decreasing cometary brightness equaled the noise of the detector, but in this scenario we argue that all the CN is inside a 10-arc-sec radius. A molecule released from the nucleus at 4:00 on 29 January—the supposed start of the outburst—would reach the outer limit of the CN observed by us at the midtime of our observations if its average velocity—hydrodynamic plus excess dissociative velocities—were 0.7 km s^{-1}. Note that HCN provides an excess velocity of 1.2 km s^{-1} to the CN radical upon dissociation (*14*) which, if the HCN were still bound to Chiron, would need to be reduced by Chiron's escape velocity, roughly 0.15 km s^{-1}. If the CN were derived from the fresh grains provided to the coma in this outburst, the velocity on dissociation would probably be somewhat smaller and the grains themselves would most likely be bound. Thus either source is consistent with the observed spatial extent of CN but with our signal-to-noise ratio it is fruitless to invert the problem and attempt to determine the velocity directly from the data.

Because in the outburst scenario all the CN is in the field of view, we can use simple analytic expressions to estimate the number of parent molecules released in the outburst. Assuming that the parents of CN are released in an impulsive burst of short duration (assumed to take place from 4:00 to 15:00 on 29 January), the total number of parents released in the outburst is related to the number of CN radicals observed some time *t* later by

$$M(\text{CN}) = M_p(\text{XCN})[1 - \exp(-t/\tau_p)] \quad (1)$$

where M_p(XCN) is the total number of CN parents released and τ_p is the mean lifetime of those parents. Again assuming that the parent molecule is HCN we find that the required outburst contains 5.2×10^{31} molecules of HCN given off at an average rate of 1.4×10^{27} molecules per second. As with the steady-state case, we assume that CO or CO_2 is ten times more abundant than the parent of CN and that it is vaporizing because it has recently been uncovered by very slow vaporization of an overlying mantle, for instance of water. In that case we find that the required area is 2.2 or 13.4 km^2, respectively—still a negligible fraction of the surface of Chiron. Again by analogy with the steady-state example, if polymeric grains are the source a smaller area is probably required.

Given the results of Luu and Jewitt (*7*), we think that the scenario of an outburst to explain the CN is the more appropriate one although clearly we cannot rule out the steady-state scenario. In the outburst, the total mass of gas ejected is 1 metric ton per second for about 10 hours. If dusty particles or icy grains are dragged out by the gas with unit dust-to-gas mass ratio, then outbursts need occur only once every several months to provide the flux of grains determined by Meech and Belton (*16*) and by Luu and

Jewitt (7). If the material is primarily icy grains, then the dust fluxes calculated by these authors must be increased (because the grains sublime slowly, even at these distances) and we would require more frequent outbursts, but they would still be consistent with the variability seen in the photometric measurements of Chiron (7, 16, 23). Our steady-state scenario also provides a mass of grains more than sufficient to replenish the grains as cited by the aforementioned authors. We believe that the photometric variability is the strongest argument in favor of the outburst over the steady-state scenario; this is dramatically confirmed by the recent announcement by Cochran and Cochran (24) that the upper limit on the abundance of CN a month before our observations was a factor of 2 lower than our measured value.

The next significant question is whether the outgassing is driven by CO or by CO_2. CO was much more abundant in P/Halley than was CO_2 but a large fraction (at least half, possibly all) of the CO came from a distributed source which could not be responsible for driving the outburst whereas CO_2 was a parent molecule (20, 22). Furthermore, CO_2 seems omnipresent in comets (based on observations of CO_2^+) whereas CO appears to vary drastically from one comet to another (25). Meech and Belton (16) chose CO in their model because it provided a higher mass-flux with which to lift grains from the surface. Because the flux of the two species differs by less than an order of magnitude for our assumed parameters of the ice, and because the lift-off of grains depends very strongly on the size-to-mass ratio of the grains, we think that the much stronger argument derives from the variability. At this heliocentric distance (11.3 AU), the vaporization of CO_2 would be at a temperature near 94 K and very sensitive to the incident insolation whereas the vaporization of CO would be at a temperature near 34 K and vary linearly with insolation; in other words, this is the "turn-on" distance for CO_2 (19). Thus pockets of CO_2 ice slightly below the surface are just reaching the temperature at which they vaporize and can drive outbursts whereas any such pockets of CO would likely have vaporized at larger heliocentric distances unless they are much deeper below the surface of the nucleus. Presumably the overall brightness surge in 1988–1990 is attributable to the accumulated coma of grains from many of these smaller outbursts. We note that Stern (10) has made some of these same points in a slightly different context.

Finally, it is also worth pointing out that outgassing from a small fraction of the surface of a comet's nucleus appears to be a characteristic of comets that have made many passages close to the sun (18), but somewhat less characteristic of comets that have not undergone many close passages. Is the localization of activity on Chiron therefore a sign of chemical heterogeneity? If so, it would indicate that cometary nuclei accreted from smaller lumps that condensed at different locations in the solar nebula.

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Constraints on the Diameter and Albedo of 2060 Chiron

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Asteroid 2060 Chiron is the largest known object exhibiting cometary activity. Radiometric observations made in 1983 from a ground-based telescope and the Infrared Astronomical Satellite are used to examine the limits on Chiron's diameter and albedo. It is argued that Chiron's surface temperature distribution at that time is best described by an "isothermal latitude" or "rapid-rotator" model. Consequently, Chiron has a maximum diameter of 372 kilometers and a minimum geometric albedo of 2.7%. This is much bigger and darker than previous estimates, and suggests that gravity may play a significant role in the evolution of gas and dust emissions. It is also found that for large obliquities, surface temperatures can vary dramatically on time scales of a decade, and that such geometry may play a critical role in explaining Chiron's observed photometric behavior since its discovery in 1977.

CHIRON HAS ELICITED CONSIDERABLE interest since its discovery in 1977 as the most distant known asteroid (1, 2). Most asteroids reside between the orbits of Mars (at 1.5 AU) and Jupiter (at 5.2 AU). Chiron ranges between 8.5 and 19 AU from the sun, crossing the orbit of Saturn. Since 1987, Chiron has been exhibiting non-asteroidal behavior, increasing in brightness more than would be expected for an airless body approaching the sun (3). Cometary activity was suspected (4–7), but no coma was seen until 1989, when it was detected in a deep CCD image by Meech and Belton (8). 2060 Chiron thus

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