Formaldehyde Kinematics and Distribution near the Cone Nebula and IR Source in NGC 2264

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Summary. We mapped the 6-cm continuum in the region of NGC 2264 and observed the 4.83 GHz H2CO absorption lines along a cross centered at the infrared position in NGC 2264 with a 2.6' telescope beam in order to examine the relationship of the infrared source, continuum and H2CO distributions. The continuum source is located at the apex of the Cone nebula 4' south of the infrared source. Of the Hα emission stars LHα 59, 61, and 62, only the latter is a conceivable source of sufficient ionization to produce the continuum emission. Another possible source is Walker’s star 178. The infrared source is certainly excluded. The H2CO cloud has its center about 5.2' north of the infrared source. The H2CO linewidths are quite large (≥ 4 km s⁻¹) in the neighborhood of the infrared and the line cannot be decomposed. There is a substantial velocity gradient of about 1 km s⁻¹ per beamwidth away from the infrared direction which might be explained in terms of the infrared source moving into the formaldehyde cloud situated behind it.

Key words: dust clouds — infrared sources — continuum sources — interstellar molecules

1. Introduction

As part of our study on the distribution of formaldehyde and its relation to infrared sources and compact H II regions, we mapped the 6-cm continuum and observed at a number of points the 4.83 GHz H2CO absorption line in the vicinity of the Cone nebula in NGC 2264 with a 2'6 beam. This region has recently attracted much interest since the discovery of an infrared source located 4' north of the apex of the Cone nebula (Allen, 1972). At this same position various mm-emission lines of molecules have been detected (Zuckerman et al., 1972; Thaddeus et al., 1972; Gottlieb and Ball, 1973; Mayer et al., 1973; Morris et al., 1974). The region was also mapped in 6-cm continuum and H2CO absorption with a 6' telescope beam by Rickard et al. (1977). Minn and Greenberg (1975) and Dieter (1976) also observed the 6-cm H2O line at the infrared position.

In all these studies the spatial distribution and relationship of the H2CO cloud with the mm molecular, IR continuum sources, and dark clouds was uncertain particularly because of inadequate resolution of the H2CO. The improved resolution provides data which may eventually help in unravelling the interrelationship of those objects.

2. Observations

The observations were made with the 100-m telescope at Effelsberg in May 1975. The beamwidth and beam efficiency of the telescope were 2.6' and 65%. The receiver was a cooled parametric amplifier with a 384-channel auto-correlator. The system noise temperature was about 70 K. The L.O. frequency was switched by 0.625 kHz so that the line appeared in both signal and reference bands. The autocorrelator was split into two 192-channel receivers and the spectra were subsequently combined. The velocity resolution is 0.2 km s⁻¹. The rest frequency 4829.660 MHz for the 1₁₂ transition of H2CO was used. The integration time ranges from 30–60 min depending on the line strength.

The 6-cm continuum measurements were made in an area of 1' × 1' around the Cone nebula. We mapped the area by slewing the telescope in declination at a rate of 15' per minute. The scan interval in right ascension is 1'/5. The integration time was 1/10s.

3. Continuum Distribution

The continuum map of the NGC 2264 region is presented in Fig. 1. A weak continuum source with an intensity of 40 m.f.u. (1 f.u. = 10⁻²⁶ W m⁻² Hz⁻¹) is found at the position of the apex of the Cone nebula. The position of the continuum peak (α2000 = 6h38m30s, δ2000 = 9°28'55") coincides closely with an Hα emission region at the apex of the cone and is about 3'3 south and 0.5' east of the infrared source. The continuum has an observed dimension of about 4' × 3' and does not extend as far as the infrared source. The strong source, shown at the northern edge of the diagram (Fig. 1) is part of OH +065 and the extended feature at the eastern edge is part of OH +067.9. Many blobs of the size of the beam or smaller are considered to be noise.

The ionizing stellar flux $N_\lambda$ of Lyman continuum photons necessary to produce the radio continuum, the excitation

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parameter $U$, the electron density $N_e$, and the optical depth $\tau$ may be calculated from the relations given by Rubin (1968) and Matsakis et al. (1976) assuming the nebula to be ionization bounded and optically thin,

$$N_e = 7.5 \times 10^{46} \frac{S \lambda^{0.1}}{d^{0.45}}$$

$$U = 13.3 \frac{S^{1.5} \lambda^{1.5} T_e^{-0.175}}{d^{0.03}}$$

$$\tau = 7.3 \times 10^{-2} \frac{S \nu^{-2} T_e^{-1} \theta^{-2}}{d^{0.5}}$$

where $S$ is the radio flux measured in flux units, $d$ is the distance in kiloparsecs, $\nu$ the frequency in GHz, $T_e$ the electron temperature in units of 10$^{10}$K, and $\theta$ the angular size in minutes of arc. From the measured radio flux and assumed distance of 800 pc (Walker, 1956) and $T_e = 7500$K, we find log $N_e = 45.4$ and $U = 3.974$. The source angular size found applying the correction for beam broadening

$$\theta_{\text{source}} = (\theta_{\text{observed}} - \theta_{\text{beam}})$$

is $\theta_{\text{source}} = 3^\prime$ in arc. The mean electron density is then $n_e = 38.3$ cm$^{-3}$ and the optical depth $\tau = 2 \times 10^{-4}$. These values are comparable with the results of the radio continuum measurements taken by Matsakis et al. (1976) at HD 147889 in the $\rho$ Oph region and by Kislyakov and Turner (1976) in L 1613 and 1640. From the calculated $N_e$, we find the exciting star must be of type B1 or earlier (Panagia, 1973).

Herbig (1953) identified the three stars at the apex of the cone, and therefore closest to the continuum peak, as Hα emission stars, LHα 59, LHα 61 and LHα 62. The positions, color indices, and magnitudes of these stars given by Herbig (1953) and Walker (1956) are listed in Table 1. We first consider if all or any of these three stars can be responsible for the continuum. Using the colors observed by Walker (1956) and assuming that the extinction follows the mean extinction law $E(U - B)/E(B - U) \approx 0.73$ we find that LHα 59 is of spectral type A0. According to van den Bergh (private communication) LHα 61 seems like a foreground object projected on (but probably close to) the nebula. If so its apparent increase in brightness is at least partly due to less extinction and its spectral type is substantially later than B0. If LHα 62 is the exciting star then its visual extinction would have to be at least 3 magnitudes larger than the visual extinction of LHα 59. Without further observations of its color nothing more definite can be stated.

Of the remaining stars in the neighborhood there is only one possible candidate, Walker’s star 178, situated about 1.5 north of LHα 59. Using the observed colors and the mean extinction law we infer that this star is of spectral type B0. However, the apparent solid angle subtended by the continuum source reduces the effective ionizing flux by at least a factor 4 to 5.

Finally we consider the infrared source. Combining the Bracket $\gamma$ luminosity, the strength of the silicate feature, and the infrared luminosity, Thompson and Tokunaga estimated that it could possibly be produced by a ZAMS star halfway between B0 and B0.5. The distance to the continuum peak is about 4$^\prime$ so that, as compared with L 178, the ultraviolet flux is reduced by a further factor of 4. This, in combination with the obvious high extinction in the neighborhood of the infrared source plus the
Table 1. Optical Properties of the Hα emission stars in the Cone and of the nearest bright star to the continuum peak

<table>
<thead>
<tr>
<th>Star Name</th>
<th>α(1950)</th>
<th>δ(1950)</th>
<th>$m^b$</th>
<th>$m_{pg}^b$</th>
<th>$B - V^a$</th>
<th>$U - B^a$</th>
<th>$A(V)^c$</th>
<th>Sp</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHa 59</td>
<td>6°38'27&quot;</td>
<td>9°29'24&quot;</td>
<td>15.22</td>
<td>15.5</td>
<td>+0.97</td>
<td>+0.66</td>
<td>5</td>
<td>A0</td>
</tr>
<tr>
<td>LHa 61</td>
<td>6°38'28&quot;</td>
<td>9°29'12&quot;</td>
<td>15.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHa 62</td>
<td>6°38'29&quot;</td>
<td>9°29'06&quot;</td>
<td>15.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>178(a)</td>
<td></td>
<td></td>
<td>7.14</td>
<td></td>
<td>-0.20</td>
<td>-0.97</td>
<td>0.3</td>
<td>B0</td>
</tr>
</tbody>
</table>

*a* Taken from Walker (1956)

*b* Taken from Herbig (1953)

*c* Assuming 800 pc distance

radio continuum limit of <0.005 Jy at 4.995 GHz (Hong and Harten, 1978) precludes the infrared object.

4. H$_2$CO Distribution

The H$_2$CO profiles obtained at the positions along a cross centered at the IR source are displayed in Fig. 2 according to their respective positions. The offsets, a beamwidth apart, are from the IR source position ($\alpha_{1950}$ = 06°38'24"9, $\delta_{1950}$ = 09°32'29")$. The line parameters (antenna temperature, half-width, radial velocity, and the equivalent width $\int dv Y_A$) are also listed in the figures.

The deepest H$_2$CO absorption is observed at the position 5°2 north of the IR source. The line intensity at this position is $-0.55$K which is exceptionally strong for dark clouds. This kind of strong absorption is normally only observed when the cloud is in front of radio continuum sources. The line intensity decreases smoothly toward the south and drops sharply at the northern positions. The line halfwidths are also exceptionally large near the IR source position as noted earlier by Dieter (1976). Rickard et al. (1977) decomposed the line into several

Fig. 2. The 6-cm H$_2$CO line profiles observed along a cross centered at the IR position, offset (0.0). Straight lines at velocities of 6.0 and 9.0 km s$^{-1}$ are drawn so that the change of the line velocity is clearly shown. The offset positions from the IR sources position, $\alpha(1950)$ = 06°38'24"9 and $\delta(1950)$ = 09°32'29" and line parameters are given
components by gaussian fitting and explained the observed large halfwidth by a composite of many lines. In the present survey, however, we are not able to justify decomposing the lines even though the noise level in our profiles is no greater than that of Rickard et al. We would like to add that even larger line halfwidths have been observed in our survey of dust complexes near NGC 7538 (Minn and Greenberg, 1975) although that region is much more extensive and probably different from the one we are considering here.

We Hanning smoothed the line profiles and measured the equivalent width $\int dv T_d$ at each position as entered in Fig. 2. The maximum equivalent width is observed at two beamwidths (5:2) north of the IR source. The overall distribution of the $H_2CO$ molecule looks quite similar to the map of Rickard et al.

5. Interpretation of the Kinematics

The radial velocity distribution of the $H_2CO$ cloud at the immediate vicinity of the infrared continuum source appears to be different from that of the surrounding region. At this source position the $H_2CO$ cloud has its maximum velocity of 7.9 km s$^{-1}$ away from us. At points removed from this in any of the four directions, the observed recessional velocity is reduced so that the velocity gradient has roughly circular symmetry. In the north, at the third offset position (0, +7:8), the velocity drops to 5.0 km s$^{-1}$. Rickard et al. observed the velocity gradient only in the north–south direction.

We note that the molecular mm lines are centered at the infrared source but with extensions as much as 5' x 6' (Morrison et al.). They have a positive velocity of about 7.5-8.5 km s$^{-1}$ (Mayer et al., 1973) which is close to the maximum velocity of H$_2$CO in the same direction. The roughly radial velocity gradient of formaldehyde centered at the infrared source then suggests, as one possibility, that there is a dense knot of material comprising the infrared source moving into a cloud and creating a bow wave such that the material containing H$_2$CO is pushed away with a recessional velocity which decreases outward from the center of the line of motion. The differential velocities of the order of 2-3 km s$^{-1}$ imply a supersonic motion with a Mach number $\geq$ 2 which for an isothermal shock produces a density enhancement $\geq$ 4. The mm molecules could be excited as a result of the compression within a shell, in the shape of the bow wave, which is produced by the moving infrared object. The velocity of the mm emission would then have a smaller radial gradient than the $H_2CO$ absorption. Further mapping of the mm emission is required to test this hypothesis.

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