Reports

Discovery of Hydroxyl Radio Emission from Infrared Stars

Abstract. *Radio spectral line emission from hydroxyl radicals has been detected from four infrared stars. The emission from the infrared star NML Cygni at 1612 megahertz is the strongest radio emission line yet detected. Sixteen other stars with infrared excesses showed no detectable hydroxyl radio emission.*

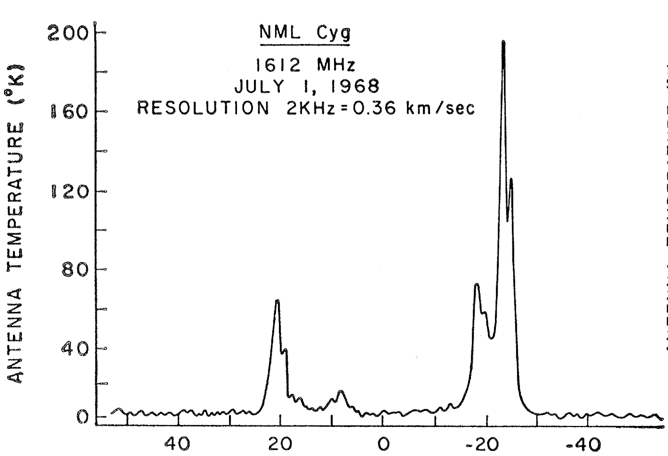
In 1965, Neugebauer, Martz, and Leighton (*1*) announced the detection of extremely cool stars having most of their radiation at infrared wavelengths; and in 1966, Ulrich *et al.* (*2*) reported on further observations of infrared stars discovered in the California Institute of Technology (CIT) survey. More recently, Raimond and Eliasson (*3*) noted the close juxtaposition of the hydroxyl (OH) radio emission source and the infrared point source of Becklin and Neugebauer (*4*) in the Orion Nebula. These facts suggested a search for OH radio emission from the so-called "infrared stars," and in this note we report the detection of intense, nonthermal, OH emission from the star NML Cyg and weaker emission from several other infrared stars.

Our initial observations were conducted with the 120-foot (36-m) radio telescope of the Haystack Microwave Research Facility of Lincoln Laboratory, M.I.T., from 21 to 29 May 1968. The observations reported here were conducted with the 140-foot (43-m) radio telescope of the National Radio Astronomy Observatory (NRAO), Green Bank, West Virginia, from 27 June to 11 July 1968. A parametric amplifier receiving system was used which gave an overall system noise temperature of 260°K at 1665 Mhz. The spectral lines data processing was done with the new NRAO 400-channel autocorrelation receiver. We emphasize that reduction of the data is still incomplete, but the results are of sufficient importance to warrant publication.

We have detected OH emission from the infrared stars NML Cyg, CIT-3, CIT-7, and NML Tau, but we were unable to detect emission from the stars TX Cam, R Mon, T Tau, RY Tau, CIT-1, -2, -4 to -6 and -8 to -14. Infrared observers have found that NML Cyg is a unique object compared to other infrared stars (*5, 6*) because of its high energy near 2.4 μ, lack of H_2O absorption lines in its spectra, an effective radiating temperature of ~700°K, and its inability to be seen in the visual, even with the 200-inch (500-cm) Palomar telescope. From our limited results, we have found that NML Cyg is also unique in its radio properties. For example, the frequency 1612 Mhz is heavily favored for OH emission from NML Cyg. The maximum antenna temperature with the NRAO 140-foot radio telescope is ~190°K, thus making this line the strongest radio emission spectral line yet detected. By contrast, the 1665 Mhz line gives a maximum antenna temperature of ~6.5°K, the 1667 Mhz line antenna temperature is 0.8°K, but the 1720 Mhz line was not detected with an upper limit of 0.5°K. Furthermore, the 1612 Mhz shows no circular or linear polarization, at least to a limit of 10 percent, whereas the 1665 Mhz line is predominantly left circularly polarized. The 1612 Mhz spectrum of NML Cyg is shown in Fig. 1, and the 1665 Mhz spectrum in Fig. 2. The spectrum is complex and therefore the statement above about the lines being essentially unpolarized may not apply to all the subfeatures apparent in Fig. 1. A summary of our observational results is presented in Table 1.

As far as we can deduce with the 18 arc min beamwidth of the NRAO telescope, the −23 km/sec and the +20 km/sec features at 1612 Mhz originate from a point source in the direction of NML Cyg. This property of the emission has not been checked for the weaker features from this source.

A summary of our observations of CIT-3, CIT-7, and NML Tau is presented in Table 1 also. The 1612 Mhz



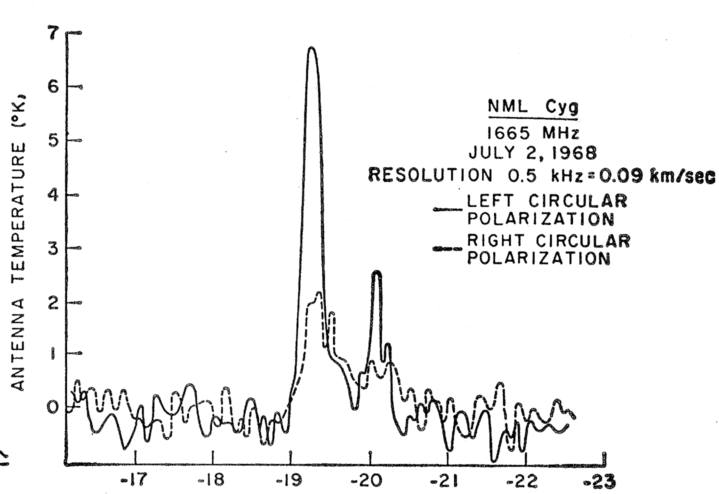


Fig. 1 (left). The 1612 Mhz spectrum of NML Cyg taken with left circular polarization. The integration time was 12 minutes. Fig. 2 (right). The 1665 Mhz spectrum of NML Cyg showing both the left (solid) and right (dotted) circular polarization. The integration times were 3.75 hours and 5 hours, respectively.

emission of CIT-3 was mapped spatially and appears to originate from a point source as that of NML Cyg. In no case was emission detected at 1720 Mhz. Our criterion for detection was a line of magnitude four times the temperature fluctuations, or more. Conversely, all upper limits quoted in Table 1 imply nothing greater than four standard deviations.

As stated, we have not detected OH emission from the infrared stars TX Cam, T Tau, RY Tau, R Mon, CIT-1, -2, -4 to -6, and -8 to -14 with an upper limit of 1°K antenna temperature. These stars were chosen for observation because of their unusual infrared properties *(2, 5, 7)*. Many of them are T Tauri or Mira-type variable stars. The velocity range searched in these observations was -90 to $+90$ km/sec, with an effective filter resolution of 2 khz, in both right and left circular polarization, at all four OH frequencies, with the following exceptions: for CIT-5 we have no data at 1667 Mhz for right circular polarization, and for CIT-6 we have no 1667 Mhz data in either polarization.

The character of the OH emission reported here seems different from any reported previously. In the past, intense, nonthermal OH emission has been reported from H II regions and nonthermal, continuum radio sources, but the infrared stars do not appear to have any detectable radio continuum associated with them. Comella searched for radio emission from NML Cyg, NML Tau, R Mon, T Tau, and RY Tau at 195, 430, and 611 Mhz with negative results which imply an upper limit of 10 flux units (*8*). Our own observations, at 1612 Mhz, set an upper limit on the continuum emission from NML Cyg and CIT-3 of ~ 3 flux units, and the observations of Downes and Rinehart (*9*) at 5000 Mhz imply an upper limit of approximately 1 flux unit for NML Cyg.

Johnson, Low, and Steinmetz (*10*) deduced an effective radiating temperature of NML Cyg in the infrared of ~ 700°K from spectral observations. Since these observers measured absolute flux densities, they could compute an angular size for NML Cyg. Their result was 0.2 arc sec, quite large for a stellar diameter. If we adopt this size for the radio-emitting region, strictly an assumption on our part, then the 190°K feature at 1612 Mhz must have a radio brightness temperature of $\sim 5 \times 10^9$ °K. This indicates a maser-type emission mechanism. Even if we make no assumption about angular size, the strong emission at 1612 Mhz and no emission at 1720 Mhz are proof of a nonthermal emission mechanism. This is consistent with a maser model consisting of near-infrared pumping of the OH molecules to an excited state, followed by far-infrared cascade to the ground state, as proposed by Litvak (*11*). Similar remarks apply to the source CIT-3.

We note that the OH emission from an infrared star seems to be concentrated in two velocity ranges. For example, as Fig. 1 clearly shows, the emission from NML Cyg is strongest at ± 20 km/sec. Other examples are CIT-3 where the emission occurs at -9.5 and $+27$ km/sec and NML Tau at $+17$ and $+51$ km/sec. This is suggestive of a rotating, or expanding or contracting, gas cloud, but more cases of OH emission associated with infrared stars are needed to establish whether there really is a distinct separation in radial velocity for each source. No emission could be seen from NML Tau at a velocity of $+63 \pm 5$ km/sec as reported (*5*), for the NML Tau optical absorption lines; however, the radio value of $+51$ km/sec is not far beyond this range.

The intense lines of NML Cyg at 1612 Mhz make this source excellent for very long base line interferometry of the type that has been used to study other OH emission regions with an angular resolution of 0.01 arc sec, or better (*12*). It should be possible to determine the angular size of the NML Cyg OH source and to establish whether both velocity components (± 20 km/sec) are spatially coincident.

Table 1. Summary of observations of OH radio emission from infrared stars; T_A, antenna temperature; RC, right circular; LC, left circular.

Line frequency (Mhz)	Antenna polarization	T_A (°K)	Velocity (km/sec)
NML Cyg -90 to $+90$ km/sec searched			
1612	RC	130	-25.1
		190	-23.9
		80	-18.5
		7	-13.0
		14	8.7
		11	10.2
		10	16.8
		37	20.5
		57	21.5
	LC	Identical to RC except at -18.5 km/sec where $T_A = 70$°K	
1665	RC	2	-19.5
		0.6?	-12.8
	LC	6.5	-19.5
		2	-20.5
		1	-12.6
1667	RC	0.8	14.3
	LC	0.8	-19.9
		0.8	14.0
1720	RC	<0.5	
	LC	<0.5	
NML Tau -90 to $+90$ km/sec searched			
1612	RC	0.8	17
		0.8	51
	LC	0.7	17
		0.7	51
1665	RC	<0.6	
	LC	<0.6	
1667	RC	0.9	15
1667	LC	0.8	15
1720	RC	<0.5	
	LC	<0.5	
CIT 3 -45 to $+45$ km/sec searched			
1612	RC	7.5	-9.5
		7.5	27
	LC	7.5	-9.5
		8.0	27
1665	RC	<0.5	
	LC	<0.5	
1667	RC	0.7	-9
		1.0	27
	LC	0.5?	-9
		1.1	27
1720	RC	<0.5	
	LC	<0.5	
CIT 7 -45 to $+45$ km/sec searched			
1612	RC	1.2	-1
	LC	1.0	-1
1665*	RC	1.0	-0.5
	LC	0.8	-0.5
1667	RC	0.5?	-1
	LC	0.6?	-1
1720	RC	<0.5	
	LC	<0.5	

* At this frequency, -90 to $+5$ km/sec was searched.

WILLIAM J. WILSON
ALAN H. BARRETT

Departments of Electrical Engineering and Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge 02139

References and Notes

1. G. Neugebauer, D. E. Martz, R. B. Leighton, *Astrophys. J.* **142**, 399 (1965). The letters NML before a star's name refer to these authors.
2. B. T. Ulrich, G. Neugebauer, D. McCammon, R. B. Leighton, E. E. Hughes, E. Becklin, *ibid.* **146**, 288 (1966).
3. E. Raimond and B. Eliasson, *ibid.* **150**, L171 (1967).
4. E. E. Becklin and G. Neugebauer, *ibid.* **147**, 799 (1967).
5. R. F. Wing, H. Spinrad, L. V. Kuhi, *ibid.*, p. 117.
6. D. McCammon, G. Munch, G. Neugebauer, *ibid.*, p. 575.
7. W. Z. Wisniewski, R. F. Wing, H. Spinrad, H. L. Johnson, *ibid.* **148**, L29 (1967); E. E. Mendoza V., *ibid.* **151**, 977 (1968); G. H. Herbig, *ibid.* **152**, 439 (1968).
8. J. Comella, *ibid.* **149**, L91 (1967).
9. D. Downes and R. Rinehart, *ibid.* **144**, 937 (1966).
10. H. L. Johnson, F. J. Low, D. Steinmetz, *ibid.* **142**, 808 (1965).
11. M. Litvak, in preparation; private communication.
12. J. M. Moran, B. F. Burke, A. H. Barrett, A. E. E. Rogers, J. A. Ball, J. C. Carter, D. D. Cudaback, *ibid.* **152**, L97 (1968).
13. Supported in part by NASA grant NGL 22-009-016. We thank the staffs of the National Radio Astronomy Observatory and the Haystack Microwave Research Facility, Lincoln Laboratory, M.I.T., for facilities and technical support. The NRAO is operated by Associated Universities Incorporated, under contract with NSF; Lincoln Laboratory is operated by M.I.T. with the support of the U.S. Air Force.

18 July 1968