No. 139 THE INFRARED SPECTRUM OF THE NML CYGNUS OBJECT*

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ABSTRACT

An infrared spectrum from 1.4 μ (7000 cm^{-1}) to 4.0 μ (2500 cm^{-1}) has been obtained for the NML Cygnus infrared star. A rapid-scanning Michelson interferometer was used. The structure of the CO bands around 4300 cm^{-1} indicates a temperature of 2000°–2500° K. As before, a large infrared excess, compared with that of giants of the same temperature, was found. A broad absorption at 3300 cm^{-1} (3.03 μ) was found; this absorption may be due to interstellar ice.

1. *Introduction*

During the past year we have put into operation a rapid-scanning Michelson interferometer-spectrometer. The interferometer is constructed for maximum efficiency at about 2.5 μ, but it can be used over the range of wavelengths from 1.2 μ (8200 cm^{-1}) to 4.5 μ (2200 cm^{-1}). The resolution of the spectra is about 8 cm^{-1}, independent of wavelength.

The new interferometer has been used to obtain infrared spectra of twenty-one stars, over the range from 1.2 to 2.6 μ (Johnson *et al.* 1968). All of these spectra were corrected for atmospheric extinction on the basis of a lunar spectrum obtained from the NASA Convair 990 Jet Aircraft Observatory flying at an altitude of 41500 feet. These published data were obtained using unrefrigerated PbS detectors. Recently, however, liquid-nitrogen-cooled PbS detectors were arranged for use with the interferometer; this modification resulted in a large increase in sensitivity and in extension of the spectra to the PbS limit of 4.0 μ (2500 cm^{-1}).

Among the objects that we have observed with the refrigerated detectors is the NML Cygnus infrared star (Neugebauer, Martz, and Leighton 1965). The spectrum of this object was observed at about 1 μ by Münch and Scargle (1965), Ford and Rubin (1965), and Wing, Spinrad, and Kuhi (1967). Longer-wavelength spectra were obtained by McCammon, Münch, and Neugebauer (1967) and Gillett, Stein, and Low (1968). The extremely red color of this object has led to the suggestion (Neugebauer *et al.* 1965) that its temperature might be about 1000° K. On the basis of their spectrum, Münch and Scargle concluded that the Cygnus object has a spectral type not earlier than M8 and that it probably is not a main-sequence object. However, Wing *et al.* (1967) found the strengths of the TiO,

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VO, and other features around 1 μ to be consistent with a spectral type of M6. Had it not been for the very red color, they would have given a definite spectral type of M6 (Wing 1966). I have argued (Johnson 1966*a*, 1967) that the observational data for this object are consistent with the hypothesis that it is a highly reddened M6 star of high luminosity (perhaps of luminosity class Ia). This interpretation means that the star has very large infrared excesses, compared with class III stars (Johnson 1967); these have also been found for early M Ia supergiants.

2. *The Temperature of NML Cygnus*

The spectrum of the NML Cygnus infrared star from 4000 to 6000 cm^{-1} is shown in Figure 1. This spectrum has been corrected for atmospheric extinction as described by Johnson *et al.* (1968); the corrections were based upon nearly simultaneous, equal-altitude transfers on two nights to the Moon and α Her.

The temperature of NML Cygnus may be inferred from the structure of the CO bands that appear in Figure 1 between 4100 and 4400 cm^{-1}. The relative strengths of the bands of this series should be temperature-dependent; at lower temperatures there should be fewer bands visible than at higher temperatures. This temperature dependence is clearly visible in the spectra of Johnson *et al.* (1968); the number of bands ranges from eight in α Boo (K2 IIIp) to five in α Her (M5 Ib–II) and four in R Hya (M6e). A recently obtained spectrum of EU Del (M6 III) shows five bands. Comparison of the spectrum of Figure 1 (which shows four CO bands) with our other spectra, both published and unpublished, indicates that the temperature of NML Cygnus is equivalent to a spectral type of about M7, a result which may be considered not to disagree seriously with M6, obtained by Wing *et al.* (1967), and M8, obtained by Münch and Scargle (1965). The temperature of the object which produces the absorption-line spectrum appears to be between 2000° and 2500° K.

Thus the new spectrum shown in Figure 1 confirms the suggestion that the NML Cygnus object is a highly reddened star, whose spectral type we now take to be M7. The reddening, E_{B-V}, is of the order of 2.2 mag. Forbes (1967) mentioned that his observations of the infrared polarization of this object also are consistent with this interpretation. Additional polarimetric observations at shorter wavelengths, by Forbes (1968) and Kruszewski (1968), show that the percentage of polarization rises with decrease in wavelength and that its wavelength dependence is similar to that of interstellar polarization (Serkowski, Gehrels, and Wisniewski 1969). NML Cygnus is too faint to measure in the visual range (5500 Å), but the observed polarization of 0.22 mag obtained by Hiltner (1956) for the nearby highly reddened, early-type star VI Cyg No. 12 is quite consistent with the observed infrared polarization and the known wavelength dependence at shorter wavelengths. Furthermore, Krusewski's recent observations show that even the *angles of polarization* of NML Cygnus and VI Cyg No. 12 are identical, within the observational errors.

3. *Is NML Cygnus A Carbon Star?*

It has been suggested, principally on the basis of the lack of H_2O absorptions, that NML Cygnus has some similarity to carbon stars (Wing *et al.* 1967; McCammon *et al.* 1967). The lack of steam absorption is confirmed by the spectrum shown in Figure 1. However, NML Cygnus does not exhibit the strong absorption at 5500–5660 cm^{-1} which appears in all four of the cool carbon stars we have observed. This strong absorption, starting at 5660 cm^{-1}, has been identified (Johnson *et al.* 1968) with the Ballik-Ramsay (1963) bands of C_2; there is no sign of this absorption in the spectrum of NML Cygnus. This fact was also mentioned by McCammon *et al.* (1967).

4. *The Nature of the NML Cygnus Object*

The interpretation that NML Cygnus is a highly reddened M7 star also leads to the conclusion that it is a high-luminosity object; the dense interstellar clouds which redden this object, VI Cyg No. 12, and other highly reddened objects in this region of the sky are some 500 pc distant (Lynds 1968). If NML Cygnus is a reddened M7 star at a distance of 500 pc, its absolute bolometric magnitude is $M_{bol} = -10.1$. This is a very high luminosity, but it is not unprecedented. For example, μ Cep (spectral type M2 Ia) has an absolute visual magnitude $M_v = -7.0$ (Blaauw 1963); its observed bolometric correction is -1.6 mag, leading to $M_{bol} = -8.6$. According to Blaauw (1963), a star of spectral type G0 Ia–O has $M_v = -9.0$; since the bolometric correction is zero, $M_{bol} = -9.0$. Also according to Blaauw, spectral type B0 Ia–O has $M_v = -8.1$; the bolometric correction is -2.3 mag (Johnson 1966*b*; other investigators find *larger* corrections), from which $M_{bol} = -10.4$.

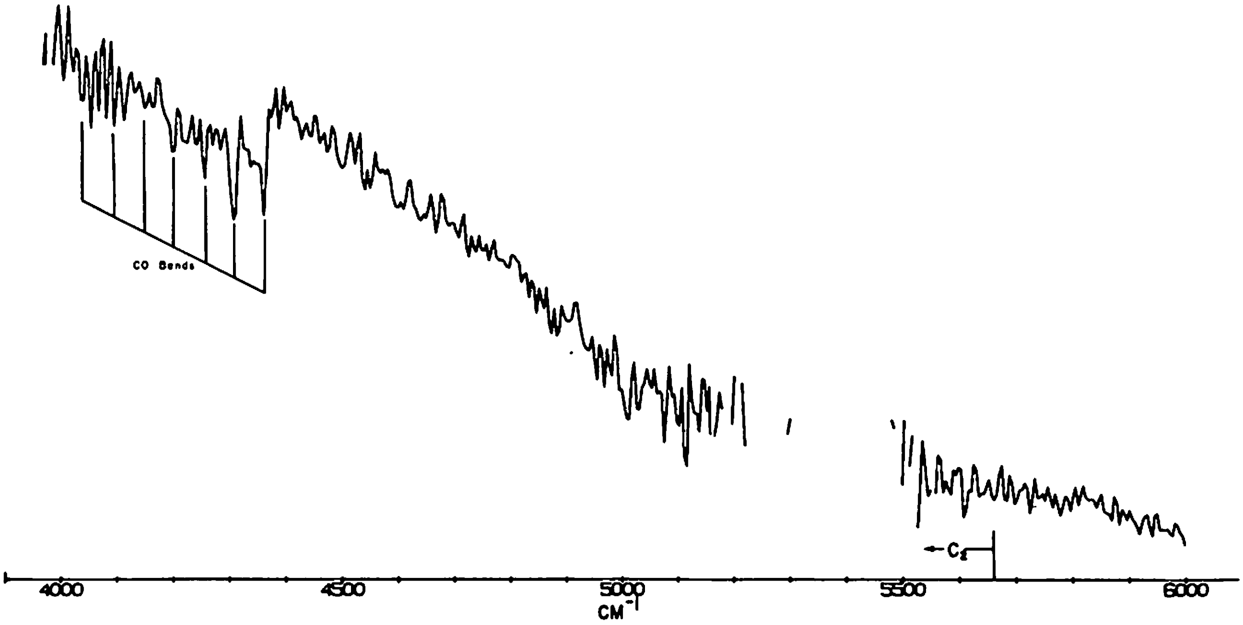

Fig. 1 Spectrum of the NML Cygnus infrared star from 4000 to 6000 cm^{-1}. Spectrum has been corrected for atmospheric extinction, as described by Johnson *et al.* (1968).

The large infrared excess could have two explanations: (1) that NML Cygnus is a binary star, one component being an M7 star and the other an infrared star, perhaps like the one discovered by Becklin and Neugebauer (1967) but much brighter; (2) that it has an extensive circumstellar cloud, probably made up of particles 10–20 μ in diameter (so that they can radiate efficiently at 20 μ), which absorbs (*neutral* absorption at the shorter wavelengths; the reddening is *not* due to this circumstellar cloud) a large fraction of the radiative output of the M7 star and re-radiates it at longer wavelengths. It could then be an object something like R Mon (Mendoza V. 1966, 1968), i.e., a protostar in the process of formation. The great luminosity implies that NML Cygnus would be a pre-O- or -B-type star rather than a pre-solar-type object. Iben (1967) has already suggested that the M supergiants in h and χ Persei are actually in the pre-main-sequence stage rather than in the post-main-sequence stage. According to his (Iben 1965) calculated evolutionary tracks for pre-main-sequence stars, a pre-O star would have a mass 15 times the solar mass and a luminosity 10^4 (10 mag) times that of the Sun.

According to Iben (1965), the duration of this stage in the star's life would be very short — less than 1000 years. In this connection, one is reminded of the sudden brightening of FU Orionis (Herbig 1966). If NML Cygnus is really a pre-O star, there is an appreciable chance that it will change within our lifetime.

5. *The Long-Wavelength Spectral Region*

If NML Cygnus is accepted as being indeed a highly reddened M7 star, it has very large long-wavelength infrared excesses. The spectral distribution of this excess out to 4 μ (2500 cm^{-1}) is shown in Figure 2; this figure shows the ratio of the NML Cygnus spectrum to those of α Her (M5 Ib–II) and EU Del (M6 III). Nearly simultaneous, equal-altitude transfers were made from NML Cygnus to these objects, so that accurate compensation for atmospheric extinction could be made. Higher weight was given to the α Her comparison because that night was the drier of the two. As in our previous publication (Johnson *et al.* 1968), the ratio is not plotted for spectral regions where the atmospheric transmission was too low for satisfactory precision.

A large infrared excess, starting at about 4500 cm^{-1} and rising toward smaller wavenumbers, is evident in Figure 2. The ratio spectrum indicates that the strengths of the CO bands around 4100–4400 cm^{-1} are slightly less than those in the comparison stars, but this could be due in part to dilution by the infrared excess. The adopted spectral type, M7, for NML Cygnus is later than that of either

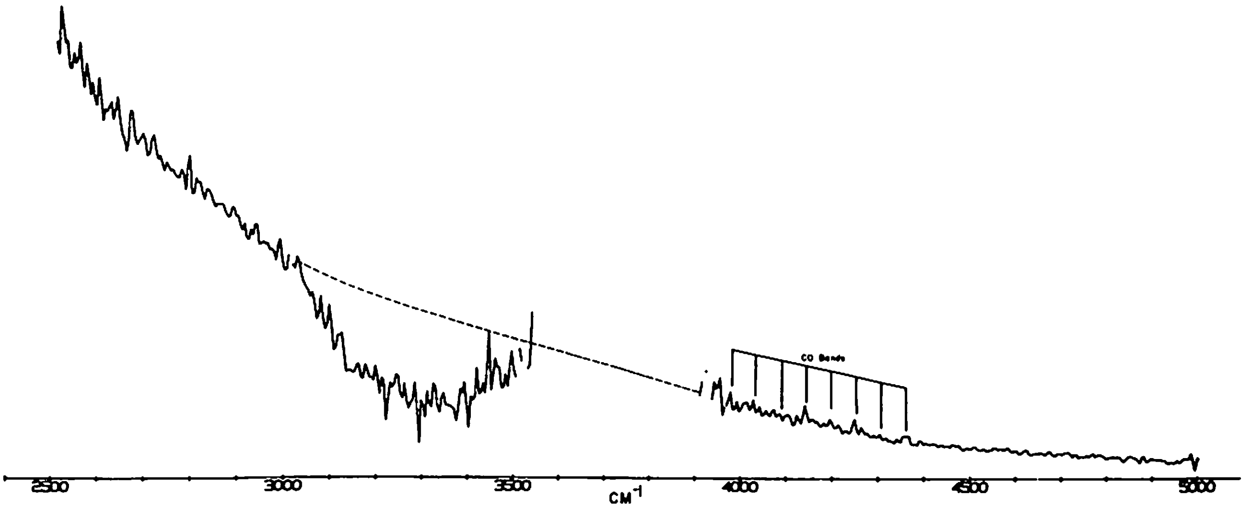

Fig. 2 Spectrum of the NML Cygnus infrared star compared with those of α Her and EU Del. This is a ratio spectrum, and all stellar features (as well as atmospheric absorptions) common to NML Cygnus and the comparison stars are therefore canceled out.

comparison star, but infrared photometry of many late-type stars (Mendoza V. and Johnson 1965; Mendoza V. 1967) shows that only a minor part of the infrared excess can be due to the difference in spectral type.

A very interesting feature of the spectrum in Figure 2 is the broad absorption feature centered at about 3300 cm^{-1}. This absorption was found earlier by Gillett *et al.* (1968), who discussed the possibility that it might be due to interstellar ice. Danielson, Woolf, and Gaustad (1965) thought that they might have detected interstellar ice in the spectrum of μ Cep, but the observed strength was considerably less than that predicted.

6. *Conclusion*

We have observed the spectrum of the NML Cygnus infrared star from 1.4 μ (7000 cm^{-1}) to 4.0 μ (2500 cm^{-1}). The structure of the CO bands near 4300 cm^{-1} indicates a temperature in accord with a spectral type of M7, i.e., somewhere between 2000° and 2500° K. No stellar steam absorptions were found, nor was the C_2 band near 5600 cm^{-1} observed.

The available data indicate that NML Cygnus is a highly reddened M7 star with large long-wavelength infrared excesses. A broad absorption, which could be due to interstellar ice, was observed around 3300 cm^{-1}. The interpretation of NML Cygnus as a highly reddened star also means that it is a high-luminosity object, because the dense interstellar clouds which redden it are at a distance of 500 pc. The great luminosity implies that, if NML Cygnus is a protostar, it is of a type earlier than O or B rather than of a pre-solar type.

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