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A search for interstellar and circumstellar C_{60}

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Summary. It has recently been suggested that the diffuse interstellar bands may be formed by ionized polyhedral carbon molecules such as C_{60}^+. While specific laboratory measurements of absorption bands of this molecular ion have not been made, a feature due to the neutral molecule C_{60} has been discovered at 3860 A. Examination of spectra of several reddened stars, as well as one star known to have circumstellar carbonaceous dust, shows no sign of the feature, leading to upper limits of order $10^{14}\,cm^{-2}$ for the column density of C_{60}. These limits are not yet sensitive enough to violate the expectations of crude predictions.

Key words: interstellar medium – molecules

1. Introduction

The diffuse interstellar bands have been an astrophysical mystery for over 50 yr. Over 40 broad absorption features ranging from 4430 Å well into the red are known (Herbig, 1965, 1988), with halfwidths as wide as 30 Å and as narrow as 1 Å. Most early hypotheses attributed the bands to interstellar dust grains, although various inconsistencies in this idea have led some to postulate a molecular origin (for a review of speculations as of ten years ago, see Smith et al., 1977).

In the past few years, renewed interest in the diffuse band problem has been stimulated by new developments in research on interstellar and circumstellar dust. First, infrared continuum measurements of reflection nebulae led to the realization that there is a population of very tiny (~ 10 Å) grains in the interstellar medium (Sellgren et al., 1983; Sellgren, 1984), which might be extremely abundant. Second, study of a family of unidentified infrared emission features seen in carbon-rich planetary nebulae, carbon-rich Wolf-Rayet stars, and in some reflection nebulae and H II regions led to the suggestion (following earlier ideas by Donn, 1968, and Duley and Williams, 1981) that large molecules of the polycyclic aromatic hydrocarbon (PAH) family might be very abundant in the interstellar medium (Léger and Puget, 1984). Observations of unresolved infrared emission features seen in broad-band IRAS data have led to the suggestion that the tiny grains and the large molecules may be one and the same species (Boulanger and Pérault, 1988, and references cited therein).

While PAH's themselves are not known to have rich optical absorption spectra, it is believed that ionized PAH's do, and it has therefore been suggested that the diffuse bands may be carried by such molecular ions (van der Zwet and Allamandola, 1985; Léger and d'Hendecourt, 1985; Crawford et al., 1985). While this is an attractive hypothesis on the basis of abundance arguments as well as spectroscopic speculation, a problem has been the wide variety of PAH ions that should exist, and the subsequent variety of expected absorption features. The diffuse bands, on the other hand, are not so numerous, and the set of features seen is quite invariant (although there is evidence that more than one carrier may be involved; Krelowski and Walker, 1987; Josafatsson and Snow, 1987).

A new, large corbonaceous molecule has recently been introduced as a contender in the diffuse band sweepstakes. Following laboratory identifications of polyhedral carbon complexes, most notably C_{60} (Kroto et al., 1985; known to chemists as "buckminsterfullerene" in reference to the geodesic dome-like structure), it has very recently been suggested that the diffuse bands may be formed by ionized C_{60} (Léger et al., 1988). While C_{60}^+ has an unknown laboratory spectrum, it is anticipated that it, like ionized PAH's, should have a rich optical absorption spectrum. The neutral species has been studied in laboratory experiments (Heath et al., 1987), which revealed an absorption band at 3860 Å. Even though C_{60} should be largely ionized under normal diffuse cloud interstellar conditions, it is reasonable to expect a significant abundance of the neutral species to exist in equilibrium; therefore, a search for a new diffuse feature at 3860 Å seems appropriate. In this paper, a first attempt to seek such a feature is reported.

2. Observations and data reduction

The wavelength of the expected feature coincides fortuitously with an interstellar gas absorption feature due to Fe I, at 3860 Å, and lies near the CN band at 3876 Å, with the result that some data already exist covering the region of interest for a search for interstellar C_{60}. In particular, observations we have made recently with the coudé spectrograph and Reticon detector on the Canada-France-Hawaii Telescope (CFHT) are useful for this purpose. The wavelength coverage (3825 Å to 3895 Å) is nearly ideal, and the signal-to-noise ratio for the observed reddened stars ranges up to several hundred. The results of the study of Fe I and CN from these data are published elsewhere (Joseph et al., 1989). Table 1 lists the stars observed.

The observations were made during two separate runs on the CFHT, one in February 1987 and the other in December 1987.

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Table 1. Observational data

Star	MK	V	$E(B-V)$	A_c(meas.)[a]	S/N	A_c(S/N)[a]	A_c/A_v
HD 21291	B9Ia	4.21	0.42	−3.2%	620	0.32%	0.25%/mag
21389	A0Ia	4.54	0.54	0.65	780	0.26	0.16
24432	B3II	6.82	0.71	−0.63	206	0.97	0.46
27778	B3V	6.17	0.40	−3.4	300	0.67	0.56
29309	B3V	7.10	0.50	−1.7	145	1.4	0.93
37903	B1.5V	7.82	0.35	−3.2	200	1.0	0.95
53367	B0IV	7.00	0.74	−1.1	130	1.9	0.86
73882	O8V	7.24	0.72	0.45	45	4.4	2.04
89353	B9:	5.34	0.1:	−0.72	370	0.54	1.80
143275	B0IV	2.30	0.16	−1.3	1540	0.13	0.30
147165	B1III	2.9:	0.40	−1.6	1550	0.13	0.092
193322	O9V	5.80	0.41	0.66	150	1.3	1.06
199579	O6Ve	5.96	0.36	1.7[b]	200	2.6[b]	2.41
HD 210072	B2V	7.65	0.53	−0.27	45	4.4	2.77

[a] See text for an explanation of the two methods used for estimating the central depth A_c. In brief, A_c (meas.) is the value obtained by comparing the observed continuum level at 3860 Å with the mean of the levels at points 8 Å to either side; A_c (S/N) is the 2 deviation for a single pixel from the continuum allowed by the data quality

[b] See comments in the text about the measurement for HD 199579

The Reticon detector is a 1 × 1872 array; using a 600 l/mm grating in second order yielded a dispersion of 0.037 Å/diode, for an effective (2-pixel) spectral resolution of 0.074 Å. Data reduction consisted of dividing out flat-field structure and assigning a wavelength scale; this was done at the University of Colorado's astrophysics data analysis facility. The data quality is extremely high, particularly for the brighter stars in the sample, where signal-to-noise (S/N) ratios as high as 1500 were achieved.

The search for a feature due to C_{60} was made difficult by the great width (8 Å FWHM) of the expected feature. For such a broad feature, the true uncertainty in measurement is dominated by uncertainty in continuum placement, rather than by the random pixel-to-pixel fluctuations (a formal error analysis yields 2-sigma detection sensitivities of order 1 mA for the best-exposed stars, which would mean that the central depth was approximately 0.01%!). Rather than discuss equivalent width measurements, it is more practical to consider the central depth, as is commonly done in diffuse band measurements involving broad features.

Figure 1 shows spectra of a few of the target stars, illustrating the difficulty of measuring a broad, shallow feature. We have quantified the search for a feature centered at 3860 Å by making formal measurements of the continuum level at 3860 Å and comparing those with measurements at points 8 Å to either side; and by estimating from the measured S/N values the maximum depth of a feature that could be present and not detected. The results of both measurement techniques are listed in Table 1.

Many of the formal measurements are negative, indicating that the continuum at 3860 Å is above the mean level set by the points 8 Å to either side. This is caused by the presence of the stellar Balmer lines Hζ (3889 Å) and Hη (3835 Å), whose wings overlap in the region of 3860 Å for stars with very strong Balmer lines, creating a local maximum in the continuum. Thus, the formal measurements of the central depth at 3860 Å are not very meaningful, unless some method is developed for renormalizing the continuum by taking out the influence of Hζ and Hη. It should be noted, however, that even where there is upward continuum curvature, the continuum is very smooth over a much broader region than the expected width of the C_{60} feature, so that a dip in this continuum would be noticeable.

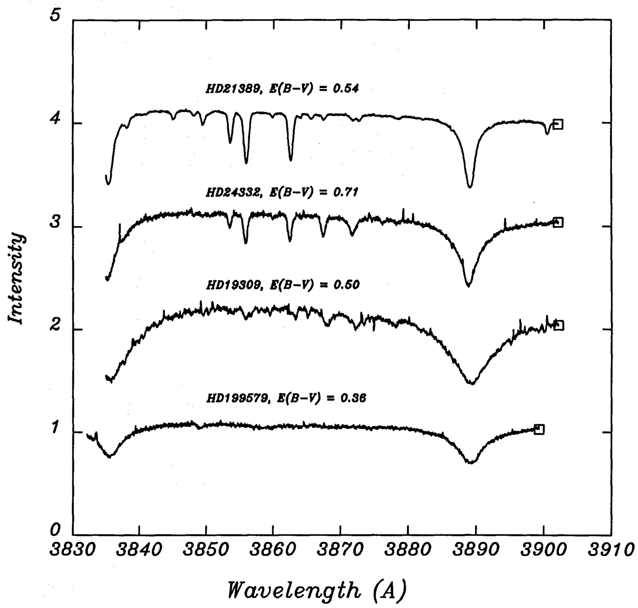

Fig. 1. Example spectra. These plots show the full 1872-element arrays obtained by the CFHT coude spectrograph's Reticon detector for four of the stars in the sample. Color excesses are indicated. The strong stellar lines at left and right are H_ζ and H_η, respectively

The limits on a 3860 Å feature which we adopt are those derived from the S/N ratios achieved, which were used to estimate how much 3860 Å absorption could be present without creating a clearly detectable dip in the continuum. We decided that the best and most objective way to do this was to adopt the formal 2-σ uncertainty at 3860 Å, based on the observed S/N ratio. This is conservative, in that we did no smoothing of the data, so that σ actually represents the probable deviation of an individual pixel

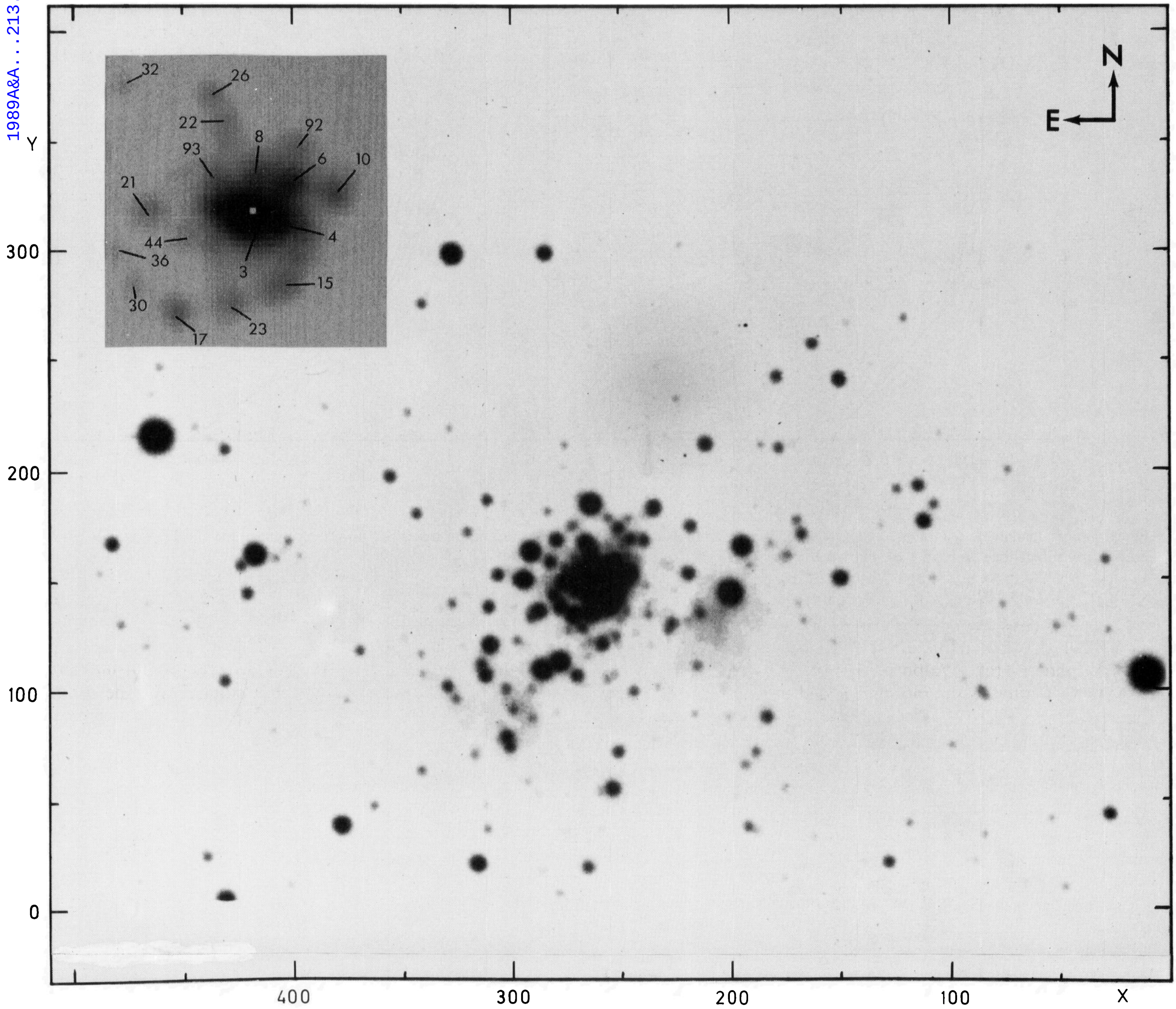

Fig. 3. Finding chart of the open cluster NGC 3603 from our B frame. The coordinates X, Y of each star are given in Table 2. The insert is an enlarged view of the central section showing the brightest stars

all stars measured is shown in Fig. 6; 88% of all cluster members lie within a circle of radius 60″ centered around HD 97950 (shown in Fig. 6) while only 29% of the suspected field stars lie within that area. Notice also that the ratio of the circle area to the total effective area covered by the CCD images is 0.22. We can thus confidently say that the radius of the ionizing cluster of NGC 3603 is $\simeq 60''$ or 2.1 pc. There are 14 stars in our sample that have $1.10 < (B-V) < 1.24$ but for which we do not have $(U-B)$ colours. Adopting the mean extinction and distance to the cluster, we find that their intrinsic colours and absolute magnitudes are consistent with them being B2 to B3 ZAMS stars and are, therefore, probably members of the cluster (see Table 2).

3.3. Cluster ages

The colour-magnitude diagrams of NGC 3603 clearly suggest that the most massive stars have evolved away from the ZAMS. In fact, the slope of the upper part of this diagram is incompatible with the ZAMS even allowing for an "abnormal" reddening law; this may be naturally explained as an age effect. We have used the theoretical isochrones of Maeder and Meynet (1987) together with Kurucz's (1979) model atmospheres to compute isochrones in the observational plane using an updated version of the code described by Melnick et al. (1985). These isochrones, for three different stellar ages, are presented in Fig. 4. There seems to be a spread of ages in the cluster with an average age of some 2–3 million years, compatible with the presence of at least two Wolf-Rayet star in HD 97950 (Moffat and Niemela, 1984). There are, nevertheless, a few optically bright stars which seem to be quite older; the most extreme case being star No. 13 (Sher No. 25), located some 18″ *north* of HD 97950, classified B1.5 Iab by Moffat (1983), that is at least four million years old. This suggests that the formation of the cluster was not strictly coeval and the isochrones

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