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THE AEROSPACE CORPORATION

FINAL SUMMARY OF RESEARCH

The Link Between UV Extinction and Infrared Cirrus

NASA/GSFC Grant NAG5-1738

Principal Investigator:

John A. Hackwell

The Aerospace Corporation

P.O. Box 92957

Los Angeles, CA 90009

(310)-336-6041

Co-Investigators:

James Hecht

The Aerospace Corporation

P.O. Box 92957

Los Angeles, CA 90009

(310)-336-7017

Ronald Canterna

The University of Wyoming

Laramie, WY 82071

(307)-766-2005

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Ronald Canterna
The University of Wyoming
Laramie, WY 82071
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Abstract

Low resolution spectra from the International Ultraviolet Explorer satellite were used to derive ultraviolet extinction curves for stars in four clusters away from the galactic plane. The extinction in three of the clusters is very similar to the general interstellar curve defined by Seaton. Stars in the fourth region, near the Rho Ophiuci dark cloud, have extinction curves that are characterized by a small "linear" term component. The star BD +36°781 is unique amongst the 20 stars observed in that it shows evidence for extinction by diamond grains near 1700 angstroms.

We used data from the final release of the IRAS Sky Survey Atlas (ISSA) to determine the 60 μm to 100 μm intensity ratio for the infrared cirrus. The ISSA data, which have been corrected for zodiacal light, gave intensity ratios that are more robust and self-consistent than for other data sets that we used.

When the infrared and ultraviolet data are combined, we see a general trend for low values of the ultraviolet "linear term" (a1) to correlate with high values of 60μm/100μm ratio. This implies that, in regions where the average dust temperature is hotter (high 60μm/100μm ratio), there is a relative absence of the small silicate grains that are responsible for the ultraviolet linear term. However, the new data do not bear out our earlier contention that the 60 μm and 100 μm emissions are poorly correlated spatially in regions where the 60μm/100μm ratio is low. Only NGC 1647 shows this result. It may be that the different dust types are particularly poorly mixed in this area.

1. Introduction

In 1991, Hackwell, Hecht and Tapia (Ap. J., **375**, 163) reported the discovery of a link between infrared cirrus emission in the 60 μm - 100 μm spectral region and ultraviolet extinction. The discovery of such a link was not entirely surprising. Infrared cirrus, which is low contrast filamentary emission that was first identified in IRAS data by Low et al. (1984, Ap. J. Lett, **278**, L9), is almost certainly associated with small dust grains having diameters smaller than 0.005 μm. Models of ultraviolet extinction also include very small dust grains.

Our earlier study (Hackwell et al., 1991, Paper 1) compared UV extinction measurements of stars in two open clusters (IC 4665 and NGC 1647) with data from the Infrared Explorer (IRAS) satellite. We found that, whereas the stars in NGC 1647 have UV extinctions that are typical of interstellar space, those in IC 4665 have a small UV "linear" term that is typical of stars found near regions of active star formation. The IRAS data showed that the infrared cirrus in IC 4665 has a significantly higher 60 μm to 100 μm color temperature than the dust in NGC 4665. We also found a high spatial correlation between the 60 and 100 μm emission from IC 4665 but found little spatial correlation at the two wavelengths for the dust in NGC 1647. We interpreted these results as implying that the dust that carries the UV "linear" term emits in the far infrared at a relatively low color temperature. When this "linear" term component is present it dominates the 100 μm emission but contributes little to the 60 μm emission. When the UV "linear" term is absent, the 100 μm emission is from the relatively hot particles that are responsible for the 60 μm emission. We further suggested that the 60 μm particles are small carbonaceous grains that are major contributors to all parts of the UV extinction except from the "linear" term. We postulated that the "linear" term is from very small silicate particles that are apparently absent in regions of active star formation.

The goal of the current work was to expand upon the earlier work by studying more lines of sight. To avoid confusion with emission from interstellar dust that is behind the clusters, we chose clusters that are at least ten degrees from the galactic plane.

2. Ultraviolet Data

Low resolution ultraviolet spectra were obtained for 23 stars in four of five proposed regions in the sky using the IUE satellite. Stars in the open cluster IC 348 could not be observed during the scheduled time because of operating constraints on the satellite. Both long-wave and short-wave spectra were taken for each object. For most stars, we used a "double offset exposure" method in which the object was offset by 11 arcseconds between shutter closing without reading the image. This increased the effective signal-to-noise ratio of an analyzed spectrum to the equivalent if two single exposures but only one camera read and refresh is required. This method was used only when the total exposure time was short enough to avoid a reduction in the overall image quality from radiation hits.

The ultraviolet data were reduced to calibrated spectra at the IUE Data Analysis Facility. UV extinction parameters were extracted from the spectra using the Massa and Fitzpatrick "pair" method (e.g. Massa and Fitzpatrick 1986, Ap. J. Suppl., **60**, 305). Table 1 summarizes the UV extinction parameters derived from the spectra. Also shown for comparison are the standard diffuse interstellar extinction curve from Seaton, results for Rho Ophiuci from Massa and Fitzpatrick (1986) and IC 4665 and NGC 1647 from Hackwell et al. (1991). The first column gives the name of the object, and the last column gives the class of the comparison star used in the analysis. Comparison stars were taken from the IUE spectral library. All of the spectra, with the exception of BD +36°781, are well fitted by the five parameters used by Massa and Fitzpatrick (1986). These are A_0, a constant background term, A_1, a term which represents the strength of a linear term, A_2, which indicates the strength of the Drude profile, A_3, which indicates the strength of the FUV curvature term, A_4, which indicates the position of the peak of the Drude profile, and A_5, which indicates the width of the Drude profile. Note the small "linear" term (A_1) for stars in the II Sco association. This is typical for dust associated with active star formation regions and agrees with our earlier results for IC 4665 which also seems to be associated with the Rho Ophiuci dark cloud.

We explored further the star BD +36°781 that is not well fitted by the Massa and Fitzpatrick parameters. Table 1 shows the extinction curves derived by using successively later spectral types, B9.5 (its nominal spectral type), A0, and A2. Although the A2 star provides the best fit, it still results in the largest linear term we have measured. In addition, all of the fits persistently show a sharp increase in extinction near 1700 angstroms. Theoretical calculations predict that small diamond grains would produce an extinction increase at this wavelength, although pure crystalline grains would produce too steep a rise. More work is needed to define the true spectral type of the underlying star. This work was presented at the "Isotopic Anomalies Workshop" held at St. Louis University in November, 1993.

3. <u>Infrared Data</u>

Infrared data were initially obtained from the Infrared Processing and Analysis Center (IPAC). The first data sets were supplied using the "BIGMAP" format which gives higher resolution than the original ALLSKY infrared maps. We found it particularly difficult to remove adequately the effects of zodiacal light from the infrared data over the small fields. As a result, we later obtained re-processed data that had the zodiacal light contribution "removed". However, even the new data had residual zodiacal light which made it difficult to find the proper zero point for the infrared surface brightness in each scene, particularly those near the ecliptic equator. We found that the derived 60 μm to 100 μm intensity ratio for many of the new scenes depended sensitively on assumptions that we made about the zero-point of the intensity in each scene. We had not had this problem with the earlier data for IC 4665 and NGC 1647 where the zodiacal light was relatively constant over the scene.

Fortunately, the final release of the IRAS Sky Survey Atlas (ISSA) became available towards the end of this project. The ISSA CD-ROM data set contains images of the entire sky as seen by IRAS with zodiacal light removed. We found that the 60 μm to 100 μm intensity ratios derived from ISSA were more self-consistent than for previous data sets. Although the authors of the ISSA warn that there may be some residual zodiacal light within 20 degrees of the ecliptic plane, the 60 μm to 100 μm intensity ratios that we derived using our techniques were not significantly changed by our additional zodiacal light corrections. Table 2 summarizes the results of processing the ISSA data for regions that surround the clusters studied with IUE. The 60 μm to 100 μm intensity region is given for a region that surrounds each star of interest together with the correlation coefficient between the 60 μm and 100 μm emissions. A high value of the correlation coefficient implies that the 60 μm and 100 μm radiation is coming from the same spatial regions. A low correlation implies that the 60 μm and 100 μm emissions originate from different areas, i.e. that the dust that is contributing most strongly to the 60 μm emission may not be the same dust that is contributing to the 100 μm emission.

4. Discussion

Table 3 summarizes the pertinent infrared and ultraviolet data for each of the clusters studied ordered by increasing value of the ultraviolet "linear term" (a1). There is a general trend for low values of a1 to correlate with high values of 60μm/100μm ratio. This implies that, in regions where the average dust temperature is hotter (high 60μm/100μm ratio), there is a relative absence of the dust that is responsible for the ultraviolet linear term. This supports the general interpretation of Paper 1 that the small silicate particles which are responsible for the "linear term", will come into equilibrium with the radiation field at a lower temperature than the carbonaceous grains. However, the new data do not bear out our contention that the 60 μm and 100 μm emissions are poorly correlated spatially in regions where the 60μm/100μm ratio is low. Only NGC 1647 shows this result. It may be that the different dust types are particularly poorly mixed in this area.

5. Summary

Ultraviolet data taken by IUE on 20 stars in four open clusters were reduced and analyzed to derive ultraviolet extinction parameters. One of the 20 stars, BD +36°781 shows evidence for extinction by small diamond particles near 1700 angstroms. Comparison of the ultraviolet data with infrared observations made by IRAS at 60 and 100 μm show that high values of 60μm/100μm emission are correlated with low values of the ultraviolet "linear term". This suggests that the particles that cause the "linear term" extinction come into equilibrium with the radiation field at relatively lower temperatures. The work is currently being prepared for publication.

Table 1

Summary of UV Extinction Parameters

Star	A_0	A_1	A_2	A_3	A_4	A_5	Sp
Collinder 463							
CR463 (7)	0.10	0.955	2.924	0.521	4.612	0.740	B8V
"	0.57	0.846	3.571	0.316	4.614	0.773	B9V
CR463 (12)	2.09	0.986	3.734	0.239	4.631	0.770	B9.5V
CR463 (5)	2.27	0.806	4.601	0.037	4.622	0.915	B9.5V
CR463 (18)	2.80	1.120	4.436	0.103	4.620	0.948	B9.5V
II Sco							
HD141637	0.97	0.603	1.864	0.074	4.609	0.717	B1.5V
HD142165	1.93	0.240	1.761	0.235	4.638	0.606	B6V
HD142883	1.75	0.174	2.564	0.092	4.595	0.721	B1.5V
HD144470	0.42	0.445	2.424	0.116	4.599	0.672	B1.5V
HD146284	1.57	0.402	2.561	0.190	4.602	0.851	B8V
HD147009	0.96	0.231	2.368	1.363	4.634	0.683	B9.5V
HD147196	1.13	0.474	2.822	0.319	4.653	0.910	B8V
HD148579	1.89	0.311	2.065	0.257	4.594	0.854	B8IV
NGC 1662							
BD+10°641	0.55	0.914	2.261	0.698	4.613	0.818	B9.5V
H5	1.14	0.873	3.099	0.658	4.602	0.856	B9.5V
H6	0.19	1.315	1.881	0.978	4.581	0.763	B9.5V
H7	1.07	0.913	2.592	1.022	4.593	0.796	B9.5V
BD+10°637	0.70	0.772	2.401	0.590	4.609	0.828	B9.5V
NGC 1342							
BD+36°710	0.49	0.903	3.107	1.713	4.608	0.885	B8III
BD+36°781	2.91	1.538	1.811	19.345	4.545	0.861	B9.5V
"	4.37	1.927	0.571	2.928	4.551	0.537	A0V
"	2.77	1.646	1.103	2.087	4.633	0.512	A2V
H8	0.80	0.885	3.526	0.983	4.625	0.946	B9.5V
Previous Work							
Seaton	0.38	0.739	3.961	0.265	4.595	1.051	
Rho Oph AB	1.64	0.139	3.349	0.349	4.594	0.969	
NGC 1647	0.16	0.791	3.004	0.976	4.638	0.902	
IC 4665	1.43	0.240	3.300	0.495	4.597	0.829	

Table 2
Summary of Infrared Results

Star	60μm/100μm	Correl, r	A1
Collinder 463			
CR463 (7)	0.164	0.913	0.900
CR463 (12)	0.155	0.878	0.986
CR463 (5)	0.134	0.811	0.806
CR463 (18)	0.157	0.717	1.120
II Sco			
HD141637	0.488	0.935	0.603
HD142165	0.617	0.740	0.240
HD142883	0.356	0.953	0.174
HD144470	0.456	0.949	0.445
HD146284	0.285	0.979	0.402
HD147009	0.289	0.908	0.231
HD147196	0.386	0.905	0.474
HD148579	0.396	0.944	0.311
NGC 1662			
BD+10°641	0.193	0.908	0.914
H5	0.192	0.821	0.873
H6	0.192	0.799	1.315
H7	0.180	0.851	0.913
BD+10°637	0.191	0.791	0.772
NGC 1342			
BD+36°710	0.092	0.788	0.903
BD+36°781	0.100	0.827	1.703
H8	0.071	0.754	0.885

Table 3

Summary

	60μm/100μm	Correl, r	A1
IC 4665	0.244	0.869	0.240
II Sco	0.409	0.914	0.360
NGC 1647	0.148	0.516	0.791
CR 463	0.153	0.830	0.953
NGC 1662	0.190	0.834	0.957
NGC 1342	0.088	0.790	1.164