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FAR-INFRARED COUNTERPART TO THE OPTICAL AND H I PLUME IN THE LEO TRIPLET OF GALAXIES: NGC 3623, NGC 3627, AND NGC 3628

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ABSTRACT

A study of the infrared emission in the Leo triplet of interacting galaxies is presented. We have applied a new background subtraction routine to *IRAS*-calibrated raw detector data (CRDD) covering a 4 deg^2 field centered on the triplet of galaxies. We report the discovery of an extragalactic IR counterpart at 60 and 100 μm to the previously known optical and H I tidal plume associated with NGC 3628. The IR plume has a ratio $I_{100\,\mu\mathrm{m}}/N_\mathrm{H}$ of $7 \pm 4 \times 10^{-15}$ Jy sr^{-1}/(H I atoms cm^{-2}), in striking agreement with Galactic cirrus clouds and a dust-to-gas ratio of 3.3×10^{-5}. We show that these values are consistent with the tidal model of the plume formation. The IR plume also exhibits a gradient of decreasing temperature along the plume away from NGC 3628 which can be explained by a dilution of the stellar optical and UV radiation field. In addition to the Leo triplet galaxies, we also detected with remarkable success almost all background late-type galaxies in the field.

Subject headings: galaxies: individual (NGC 3623, NGC 3627, NGC 3628)— galaxies: interactions — galaxies: intergalactic medium — infrared: sources

1. INTRODUCTION

The Leo triplet of galaxies, NGC 3623, NGC 3627, and NGC 3628, is believed to be a tidally interacting system. Evidence of interaction was first noted by Zwicky (1956) and Arp (1966). However, it was not until the modeling of Toomre & Toomre (1972) of tidal forces between orbiting galaxies that the suggestion arose that it was probably NGC 3627, in an eccentric orbit around NGC 3628, that induced the perturbations that led to the disturbed nature of this system. A faint optical plume extending approximately 45′ east of NGC 3628 (Kormendy & Bahcall 1974) was later found to be coincident with a neutral hydrogen filament, detected by Rots (1978). A higher resolution and sensitivity study by Haynes, Giovanelli, & Roberts (1979) confirmed the extended distribution of H I in the plume and also revealed the possible existence of H I to the south of NGC 3628 in the direction of NGC 3627. However, the southern extension to NGC 3628 has not been confirmed by new VLA observations (P. N. Appleton, in preparation). Rots also performed test particle simulations of the interaction of NGC 3627 and NGC 3628 and showed that gravitational forces alone could produce an extended linear feature resembling the plume closely both in the distribution of the gas and stars and the gross kinematics of the gas.

Since it is likely that the plume and the southern H I extension of NGC 3628 are caused by a tidal interaction, it is also probable that dust, originally mixed with the gas has also been stripped out of the individual galaxies. Such a possibility led us to search for, and find, a far-infrared (FIR) counterpart to the intergalactic H I plume in the Leo system. The detection of this FIR emission, which we assume is from the thermal reradiation of dust grains, has implications for the origin of similar H I plumes found in other nearby groups (Haynes, Giovanelli, & Chincarini 1984) and leads to some interesting conclusions regarding the physical conditions of low density H I. We will assume throughout this paper a distance to the Leo triplet of 6.7 Mpc (de Vaucouleurs 1975).

2. OBSERVATIONS

2.1. *IRAS Data Reduction*

We present 60 and 100 μm FIR data from the *IRAS* satellite. We also analyze the 12 and 25 μm data, but these will not be described in detail here. The *IRAS* mission, instrumentation, calibration, and data products are described in the *IRAS* Explanatory Supplement (1985). Calibrated Raw Detector Data (CRDD), held at Rutherford Appleton Laboratory, U.K., were dearchived. A total of 18 focal-plane scans of length 115′, centered on $11^\mathrm{h}19^\mathrm{m}00^\mathrm{s}$, 13°54′00″ (1950 epoch) were extracted. The individual scans were destripped to normalize the calibration of each detector in the survey focal plane. The scans, running from north to south along the position angle of 204′ degrees, covered approximately a 4 deg^2 field. Two independent Hours Confirmed (hereafter HCON) crossings of the region were available separated by 11 days in time and differing in scan orientation angle by 1°.6.

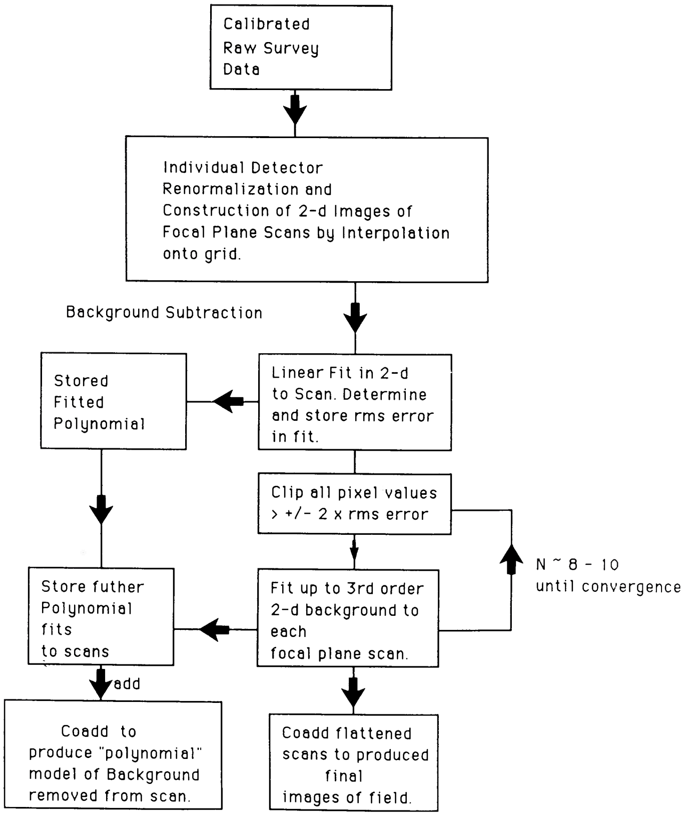
A new rigorous fitting routine was applied to the underlying infrared background on a scan-to-scan basis to reveal any extended low surface brightness features in the *IRAS* raw data. The flow diagram of Table 1 shows the three stages in which backgrounds were subtracted from each scan and finally combined to form a composite map of the Leo region.

In stage 1, a linear two-dimensional surface was subtracted from a particular scan as a first approximation to the background. Using the rms residual value for this very rough fit, any pixels greater than $\pm 5\,\sigma$ were removed from the scan.

In stage 2, the residual scan from stage 1 was used as the input to an iterative procedure in which a third-order poly-

TABLE 1

FLOW DIAGRAM



nomial was fitted to each scan. A bicubic spline routine was used to derive a least-squares surface to the residual scan. This surface was subsequently subtracted, leaving a new residual scan. However, after only one iteration this process often left a background which was biased by bright point sources in the field and so further fitting was required. This was achieved by clipping the histogram of the residual pixel values at the $\pm 2\ \sigma$ level. It was found that typically seven iterations of the above method were required before the histogram of residuals showed no significant skewness and its standard deviation converged.

In stage 3, the final background subtracted scans in each band were regridded and co-added to produce a final map of the 4 deg^2 field. The pixel sizes of the 60 and 100 μm maps, were 0.′5 and 1.′0, respectively. The estimated rms noise, based on sample regions in the final maps, for both band 3 and 4 was 0.036 ($\pm$0.001) $\times 10^6$ Jy sr^{-1}. An important parallel process to the production of the final maps of the Leo region was the construction of a composite "model" of the background which has been removed from each scan. The subtraction of up to third order polynomials from each scan may have removed some large-scale structure from the raw data. For example, we expect that, in addition to the smooth zodiacal light and any instrumental baseline drifts, the contribution to the sky background from low-level cirrus and any extended but faint structure associated with the Leo triplet would be removed by our algorithm. In order to show precisely what our subtraction algorithm has removed from, or added to the final map, we saved the individual background polynomial models from each scan and co-added them to produce a *background map* of the Leo field. We note that the sum of this map with the final Leo image will result in a return to the image that would have been created if the raw scans had been combined without any additional processing. Gray-scale maps of these *background models* are shown in Figures 1*a* and 1*b* (Plate 12) for the 60 and 100 μm, respectively. The 60 μm polynomial models show a very smooth uniform composite background with little structure. This confirms that the polynomial subtraction has not removed much small-scale astronomical structure from the individual scans. Additionally, Figure 1*a* shows that good background continuity is obtained from one scan to the next. On the other hand the 100 μm background map of Figure 1*b* shows more structure than at 60 μm. It is clear that at 100 μm some low-level structure is present on the scale of 25′–40′ which seems to be concentrated toward the Leo system. We believe that this structure is an oversubtraction of the backgrounds near the bright galaxies. However, although these maps show that we have fitted out some low-level, large-scale structure at 100 μm, the resultant maps have good linearity which are now well suited for the study of structure on a scale $<20'$. In particular in the region of the optical plume to the east of NGC 3628, the background fits at both 60 and 100 μm are remarkably flat, giving us confidence that the detection of an extended feature in this region is not adversely effected by the background subtraction algorithm.

2.2. *Optical Reduction*

The optical data for the plume near NGC 3628 comes from two sources. The first is a plate of the Leo triplet of Galaxies from the Second Palomar Sky Survey (SPSS) which is presently ongoing with the 48 inch (1.2 m) Oschin Schmidt Telescope at Palomar Observatory. This plate was a 75 minute exposure, grade A, IIIa-J plate taken through a GG385 filter and had been hypersensitized for several weeks using a hydrogen/nitrogen soaking system at room temperature. The Leo triplet lies near the edge of the original plate and shows a background gradient. Using the technique outlined by Malin (1981), we enhanced the region around the plume in a high-contrast copy, shown in Figure 2 (Plate 13) and have therefore lost the details of the faint emission in the region to the south of NGC 3628. Figure 2 shows the clear detection of the optical plume extending to the northeast of NGC 3628. The faintest features visible in Figure 2 are at the 27.5 mag arcsec^{-2} level, while the highest surface brightness features are saturated. Since high-contrast plates cannot be calibrated directly in a straightforward manner, a mosaic of CCD frames was taken in 1988 February for determining colors and luminosities of the main body of NGC 3628 and the plume. These data were taken on the Palomar (f/8.8) 1.5 m telescope. The photon collector was a RCA CCD of 320 $\times$ 512 pixels resulting in an image field size of 1.2 $\times$ 2.0 arcmin^2. The data were imaged through Johnson *B* and *V* filters for 300 s each and calibrated using the standards stars of Landolt (1983). The software package ARCHANGEL was used for reduction of the raw CCD data.

3. RESULTS

The total plume was visually measured on the original IIIa-J plate from the SPSS to be 25″ in length and 1.′5 in average width. From the CCD mosaic, it was determined that the average surface brightness of the plume is 26.5 *V* mag arcsec^{-2}, which gives it a total apparent magnitude of 13.6 $\pm$ 0.2 and an optical luminosity of 1.71 $\times 10^8\ L_\odot$ (see Table 3). Since NGC 3628 has a blue magnitude B_T^0 of 9.47, then the plume is only

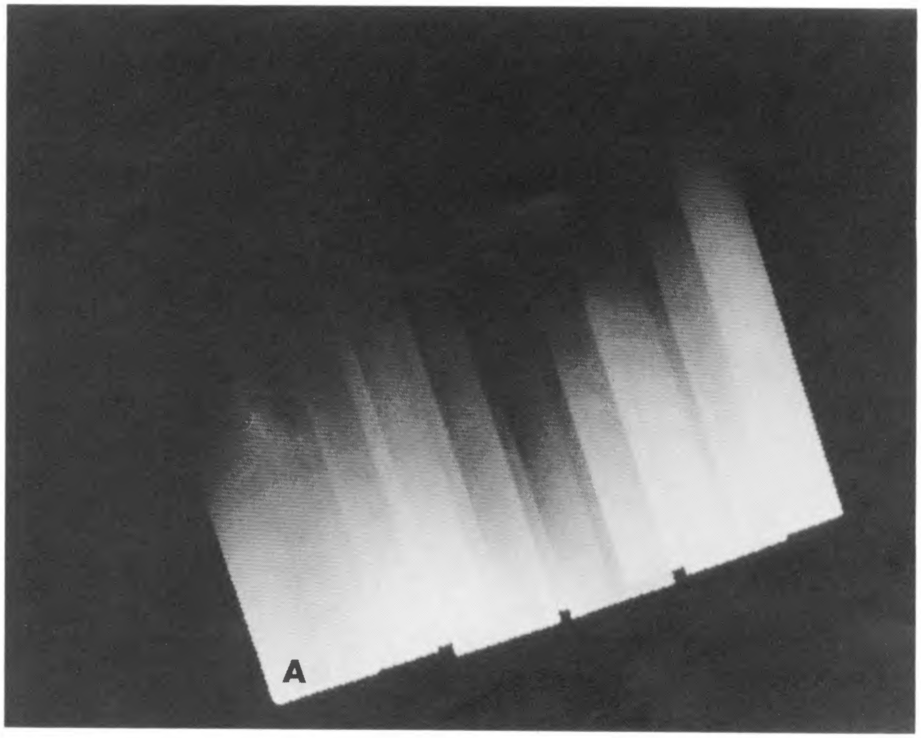


FIG. 1*a*

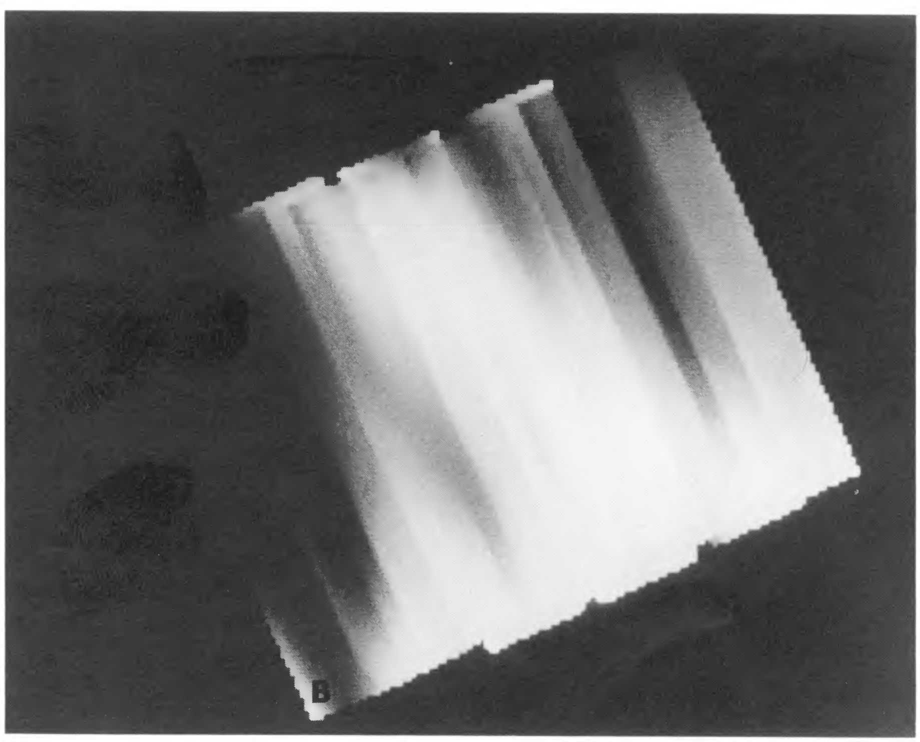


FIG. 1*b*

FIG. 1.—(*a*) Gray scale representation of the composite background map obtained by removing and co-adding polynomials from *IRAS* focal plane CRDD survey data for the 60 μm wavelength Leo triplet field. (*b*) The same as (*a*) for the 100 μm wavelength data.

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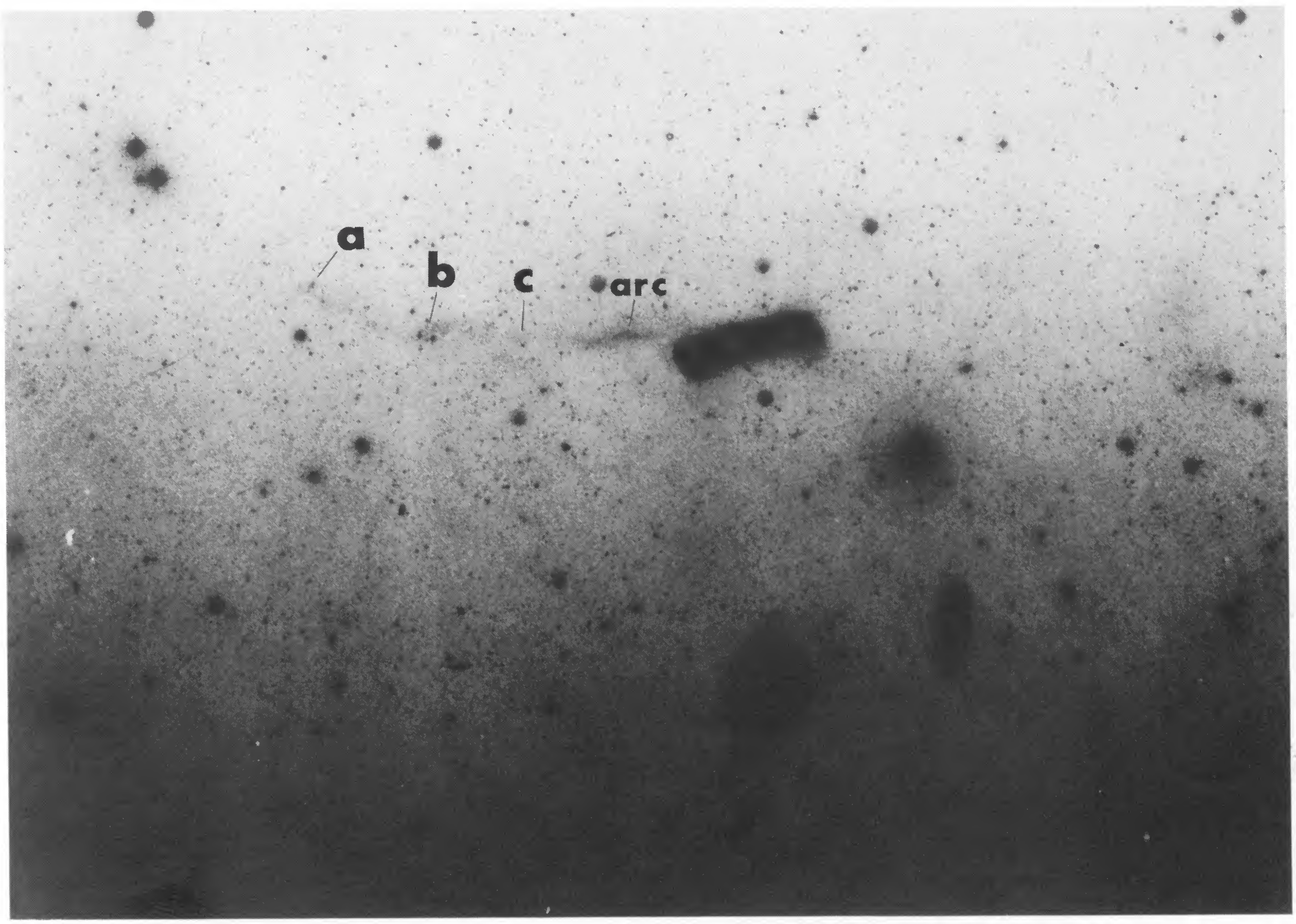

FIG. 2.—A high-contrast copy from a IIIa-J plate taken from the Second Palomar Sky Survey (SPSS). The plate has been specially enhanced in the region of the optical plume associated with NGC 3628. Table 2 shows the optical colors of the regions indicated in the plume.

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TABLE 2

OPTICAL SURFACE BRIGHTNESS AND COLOR OF SELECTED REGIONS WITHIN THE STELLAR PLUME[a]

Region	Peak Surface Brightness (V mag arcsec^{-2})	$(B-V)$ Color (mag)
A	25.1	0.51 ± 0.18
B	25.0	0.75 ± 0.21
C	25.8	0.68 ± 0.22
"Arc"	23.5	0.71 ± 0.20

[a] See Fig. 1.

2% the luminosity of the galaxy. This is similar to other tidal plume luminosities for interacting Arp galaxies from Schombert, Wallin, & Struck-Marcell (1990).

Both the high-contrast plate and the CCD mosaic clearly indicated the plume is not completely uniform in surface brightness. Four regions, identified in Figure 2, were selected for detailed analysis, and their colors and surface brightness are given in Table 2.

They were found to have similar mean colors to that of the whole plume of $B-V = 0.6 \pm 0.19$. Although these regions have $B-V$ colors which are much bluer than the average color of NGC 3628 ($B-V = 0.89$; Longo & de Vaucouleurs 1983), this is due primarily to the fact that NGC 3628 is heavily reddened by its prominent dust lane. In fact, these colors are similar to the $B-V = 0.6$ value expected for a population in a Sbc disk when the effects of dust reddening are removed, and, as a color map of the outer regions of NGC 3628 confirmed, this was indeed the mean color of the disk. Despite the blue colors, there was no evidence of any large star-forming complexes (i.e., high surface brightness H II regions) in any of the CCD frames of the NGC 3628 plume.

Figures 3*a* and 3*b* show the final 60 and 100 μm maps of the Leo field. All three galaxies are strongly detected in both bands. Integrated FIR fluxes calculated for the Leo triplet galaxies at all four wavelengths, along with additional optical properties, are given in Table 3. The dominant source of error is that of the internal calibration of the data (see *IRAS* Explanatory Supplement 1985). The color temperature of the galaxies was calculated from a modified Planck function, assuming a dust emissivity $\epsilon \propto \nu^1$. The far-infrared flux $F_{\rm FIR}$, as determined by an ideal bandpass, is calculated as

$$F_{\rm FIR} = 1.26 \times 10^{-14}\{[2.58 \times f(60)] + f(100)\}\ {\rm m}^{-2}{\rm W\ m}^{-2}\ , \quad (1)$$

where $f(60)$ and $f(100)$ are the measured fluxes at 60 and 100 μm in Jy, respectively.

The values for $L_{\rm FIR}$ are probably underestimates of the total infrared emission since they ignore the possible contribution outside the bandpass (see Cataloged Galaxies in the *IRAS* Survey 1985). Our FIR fluxes of NGC 3628, NGC 3627, and NGC 3623 estimated from the high-resolution *IRAS* maps are 20%, 65%, and 69% larger than those quoted in the *IRAS* Point Source Catalog (1985). This is to be expected since all these sources are extended compared to the individual *IRAS* point source templates given for 60 and 100 μm detectors (*IRAS* Explanatory Supplement 1985). The results compare well with the fluxes found by Rice et al. (1988) in their study of large nearby galaxies which included the Leo triplet.

Apart from the Leo triplet galaxies all other sources in Figs. 3*a* and 3*b* can be best described by splitting them into two categories: (1), unresolved point sources and (2) extended emission.

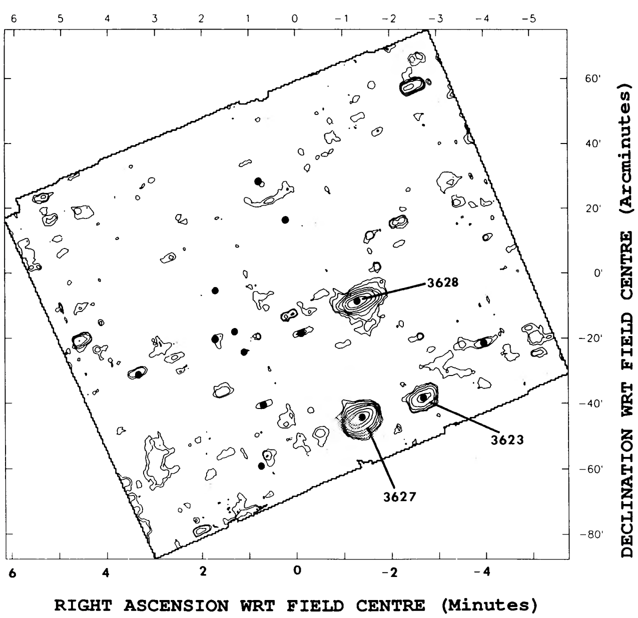

FIG. 3*a*

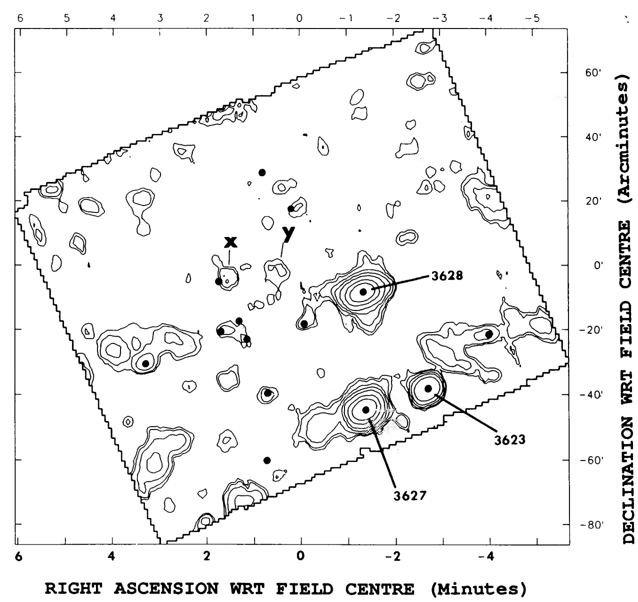

FIG. 3*b*

FIG. 3.—(*a*) The 60 μm *IRAS* image of the Leo triplet after processing focal-plane survey data with the algorithm described in the text. The principal members of the Leo triplet are indicated by NGC number, and the black dots represent the catalog positions of all Zwicky galaxies in the field. Contour levels are 0.11, 0.18, 0.36, 0.72, 1.8, 7.2, and 18 $\times$ 10^6 Jy sr^{-1}. (*b*) The 100 μm *IRAS* image of the Leo triplet. The emission regions marked X and Y are discussed in the text. Contours are same as Fig. 3*a*.

TABLE 3

OBSERVED AND INFERRED PROPERTIES OF THE LEO TRIPLET

NAME (1)	TYPE[a] (2)	B_T[b] (mag) (3)	$L_B/L_\odot$ (10^9) (4)	$(L_{FIR}/L_\odot)$[c] (10^9) (5)	IRAS FLUXES (6) 12 (Jy)	25 (Jy)	60 (Jy)	100 (Jy)	log (F_{60}/F_{100}) (7)	log (L_{FIR}/L_B) (8)	T_c[d] (K) (9)
NGC 3628 = VV 308	Sbc	9.47	7.0	5.0	3.6	6.0	55.9	132.0	−0.15	−0.37	34
NGC 3627 = M66	Sb(s)II	9.26	8.5	5.9	5.9	9.2	65.4	152.2	−0.016	−0.37	34
NGC 3623 = M65	Sa(s)II	9.59	6.3	0.54	0.9	0.7	4.7	18.5	−1.05	−0.60	28
Plume	...	13.5	0.17	0.11	...	...	1.3	3.33	−0.19	−0.41	33

[a] Types from the Revised Shapley Ames Catalogue (RSA) (Sandage and Tammann 1981).
[b] From de Vaucouleurs, de Vaucouleurs, and Corwin 1976.
[c] Calculated assuming a distance of 6.7 Mpc (de Vaucouleurs 1975) and that $L_B = 4\pi D^2 F_\lambda$ w, where $F = 4.4 f_\lambda(B)$ w m^{-2} and $\log f_\lambda(B) = -0.4 M_{B_T} - 8.17$ (Allen 1976).
[d] Assumes dust emissivity $\varepsilon \propto \nu^{-1}$.

We shall discuss category (1) first and then return to the topic of extended emission in § 3.2.

3.1. *FIR Point Sources*

Due to the nature of the background subtraction algorithm our maps are particularly sensitive to faint compact structure. Most of the 26 point sources detected at 100 μm were above a 5 σ threshold of which 12 were detected at the same level of significance at 60 μm. Using an overlay of the 100 μm map on the high-contrast SPSS plate, it was apparent that a possible correlation existed between easily identified background Zwicky galaxies (Zwicky, Herzog, & Wild 1961) and 100 μm point sources. The emission centroids for all point sources detected in the 100 μm map are listed in Table 4. We associate a source with a Zwicky galaxy in Table 4 if the 100 μm emission centroid falls within 30″ of the cataloged position of the galaxy. This is consistent with the known pointing uncertainty of the satellite. Figure 3*b* shows that nine of the 14 Zwicky galaxies were detected at 100 μm. Those Zwicky galaxies that were not detected were predominantly of early type. The correspondence of galaxies with the 60 μm point sources (see Fig. 3*a*) was poorer since only the brightest galaxies were detected. However, no galaxy was detected at 60 μm which did not have a counterpart at 100 μm.

For those unidentified 100 μm point sources we searched the Catalogue of Infrared Observations (Gezari, Schmitz, & Mead 1987) to extract all cataloged stars of spectral type from A2 to K5. However, no correlation was found with the *IRAS* data in any of the four bands. While the nature of these sources remains uncertain, it is known that a number of unidentified *IRAS* point sources are associated with distant galaxies (Heiles et al. 1987).

3.2. *Search for a FIR Counterpart to the* H I *Plume*

In addition to the point sources, some extended emission in the Leo system is evident particularly at 100 μm. Such emission is not unexpected since it is well known that Galactic "cirrus" is seen at almost all Galactic latitudes. Slices taken across the full extent of the maps along the position angle of the ridge line of the H I plume clearly revealed some low-level extended emission to the east of NGC 3628.

In order to investigate the possibility of a low surface brightness FIR counterpart to the H I plume suggested by our preliminary investigations, we smoothed the 100 and 60 μm maps

TABLE 4

ZWICKY IDENTIFICATION AND POSITION OF GALAXIES IN THE LEO TRIPLET FIELD

ZWICKY GALAXY	CATALOG POSITION R.A. (1950)	CATALOG POSITION Decl. (1950)	IRAS EMISSION CENTROID 100 μm R.A. (1950)	100 μm Decl. (1950)	60 μm R.A. (1950)	60 μm Decl. (1950)
067.050..........	11[h]15[m]00[s]	13°39′	11[h]15[h]00[s].2	13°38′44″	11[h]15[m]00[s].1	13°38′44″
067.054..........	11 16 18	13 22	11 16 22.1	13 21 48	11 16 20.0	13 21 48
067.057..........	11 17 36	13 16	11 17 36.6	13 15 51	11 17 38.8	13 15 51
067.058..........	11 17 42	13 52	11 17 40.3	13 51 50	11 17 44.6	13 50 52
067.059..........	11 18 54	13 42	11 18 50.6	13 42 56	11 18 48.6	13 42 21
0.67.061[a]	11 19 12	14 17	11 19 02.8	14 17 54	...	...
067.003..........	11 19 42	13 00	...	...	...	...
067.064..........	11 19 42	13 21	11 19 43.8	13 19 53	11 19 40.1	13 19 51
067.065[b].........	11 19 48	14 29	...	...	...	...
067.067[c].........	11 20 00	13 36	...	...	...	...
067.068[c].........	11 20 18	13 43	...	...	...	...
067.069..........	11 20 42	13 40	...	...	...	...
067.070[a].........	11 20 42	13 55	11 20 33.5	13 55 00	...	...
067.072..........	11 22 18	13 29	11 22 20.0	13 29 49	11 22 20.4	13 29 46

[a] No 60 μm counterpart to the 100 μm emission is detected.
[b] No emission at 60 or 100 μm is detected at the cataloged position of these sources. The galaxies appear optically to be of early type.
[c] These are too close together to allow meaningful measurement of the *IRAS* emission centroids.

with a Gaussian of FWHM of 12′ yielding maps with an effective spatial resolution of 13′. Before smoothing the maps, we first removed the point sources which we identified with the Zwicky galaxies, with the exception of the Leo triplet galaxies. However, the removal of the Zwicky galaxy sources was found to make an insignificant difference to the appearance of the smoothed maps because they were both weak and compact. Figures 4*a* and 4*b* show the resulting smoothed maps. Most of the fine structure (including unidentified point sources) has been smoothed below our lowest contour level. The striking result from this procedure is the clear FIR counterpart to the H I plume associated with NGC 3628. The high degree of correlation between the H I and the new 100 μm feature is shown in Figure 5 (Plate 14) where the H I surface density map of HGR is shown superposed on a grayscale representation of Figure 4*b*. A remarkable correspondence is found in both the linear extent and the position angle of the filament as seen in H I and in the FIR. The FIR plume, measured from its tip to the point at which it merges with the smoothed emission from NGC 3628 is approximately 25′ in length. We will argue later that the plume is also observed to extend farther in toward the galaxy on the full resolution maps. The reality of this FIR plume is further demonstrated by the detection of the same feature at 60 μm (see Fig. 4*a*). We find that the integrated flux of the IR plume at 100 μm is approximately 3 Jy detected over a solid angle of 2.2×10^{-5} sr. Only 60% of this flux is associated with the two sources (X and Y of Fig. 3*b*) seen on the unconvolved map, approximately 40% coming from a more diffuse component. This point will be discussed further in § 5.

In Figures 6*a* and 6*b*, (Plate 15) we also show the 100 μm high-resolution and smoothed maps, respectively, superposed on the high-contrast print taken during the SPSS. The 100 μm emission from the plume terminates precisely at the end of the faint optical plume. The 60 μm emission on the other hand does not extend all the way to the end of the plume but seems more highly correlated with the brighter inner portion of the optical plume. Here, very faint optical extension to the plume, mentioned by HGR, is not present in the 60 μm map.

The full-resolution 100 μm map shows some interesting structure to the northeast of NGC 3628 at the base of the H I plume. Figure 6*a* clearly shows a ridge of FIR emission that coincides with the bright optical stellar filament or "arc" to the NE of NGC 3628 seen on the optical plate (Fig. 2). The estimated integrated 100 μm flux from this feature is 0.67 Jy. The CCD observations indicate that this is the brightest part of the optical plume. It has a surface brightness at V of 23.5 mag arcsec^{-2} compared with an average value of 26.5 mag arcsec^{-2} in the extended plume. The $B-V$ color for the "arc" is 0.71 mag. Although the feature is relatively fainter at 60 μm than at 100 μm, the fact that the "arc" is bright at both optical and FIR wavelengths strongly suggests that the heating mechanism for the dust in the plume is local heating by stars. We return to this point later.

In what follows we will assume that (1) the FIR plume associated with NGC 3628 is indeed an extragalactic infrared counterpart to the H I optical plume and (2) the FIR flux is the thermal reradiated emission of dust grains associated with the atomic gas in the plume and heated by the stellar radiation field. The important question of whether the FIR plume is the chance alignment of a foreground galactic cirrus feature with the background group of galaxies will be discussed in § 4.

An interesting feature in the full resolution maps of Figures 3*a*, and 3*b* is extended emission to the south of NGC 3628 at 100 and 60 μm. This is coincident with the claimed southern H I extension as detected by HGR. The spatial correlation between the H I and the emission at 60 and 100 μm is very good. However, it is possible that this emission is a result of "hysteresis" in the detectors as a result of the bright emission from the galaxy. In addition, examination of the new optical material reveals two spiral galaxies to the south of NGC 3628

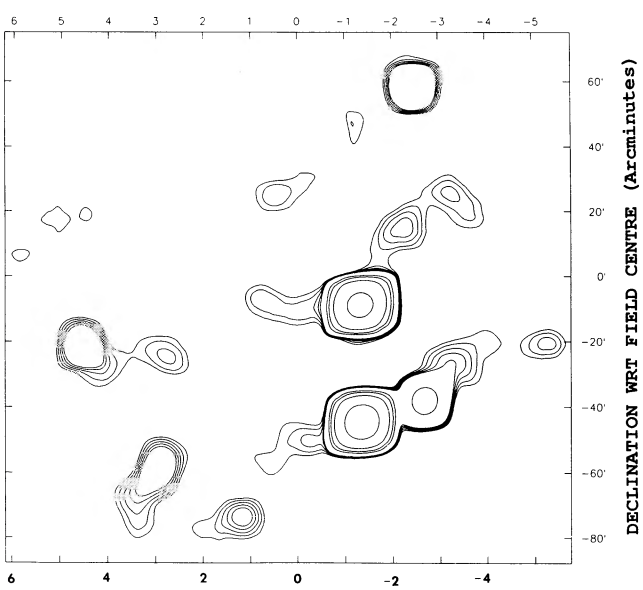

FIG. 4*a*

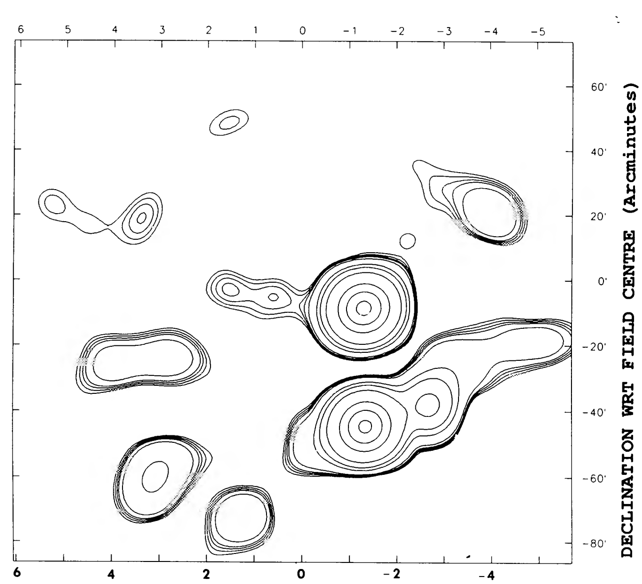

FIG. 4*b*

FIG. 4.—The result of convolving Figs. 3*a* and 3*b* with a circular Gaussian to enhance the detection of low surface brightness emission (see text). After convolution, a point source would have a FWHM of 13′. (*a*) 60 μm smoothed *IRAS* image. Contour levels are 0.03, 0.04, 0.05, 0.06, 0.07, 0.3, 0.5, 1, and 3×10^6 Jy sr^{-1}. (*b*) 100 μm smoothed *IRAS* image. Contour levels are 0.04, 0.05, 0.06, 0.07, 0.1, 0.3, 0.5, 1, 3, 5, & 7×10^6 Jy sr^{-1}.

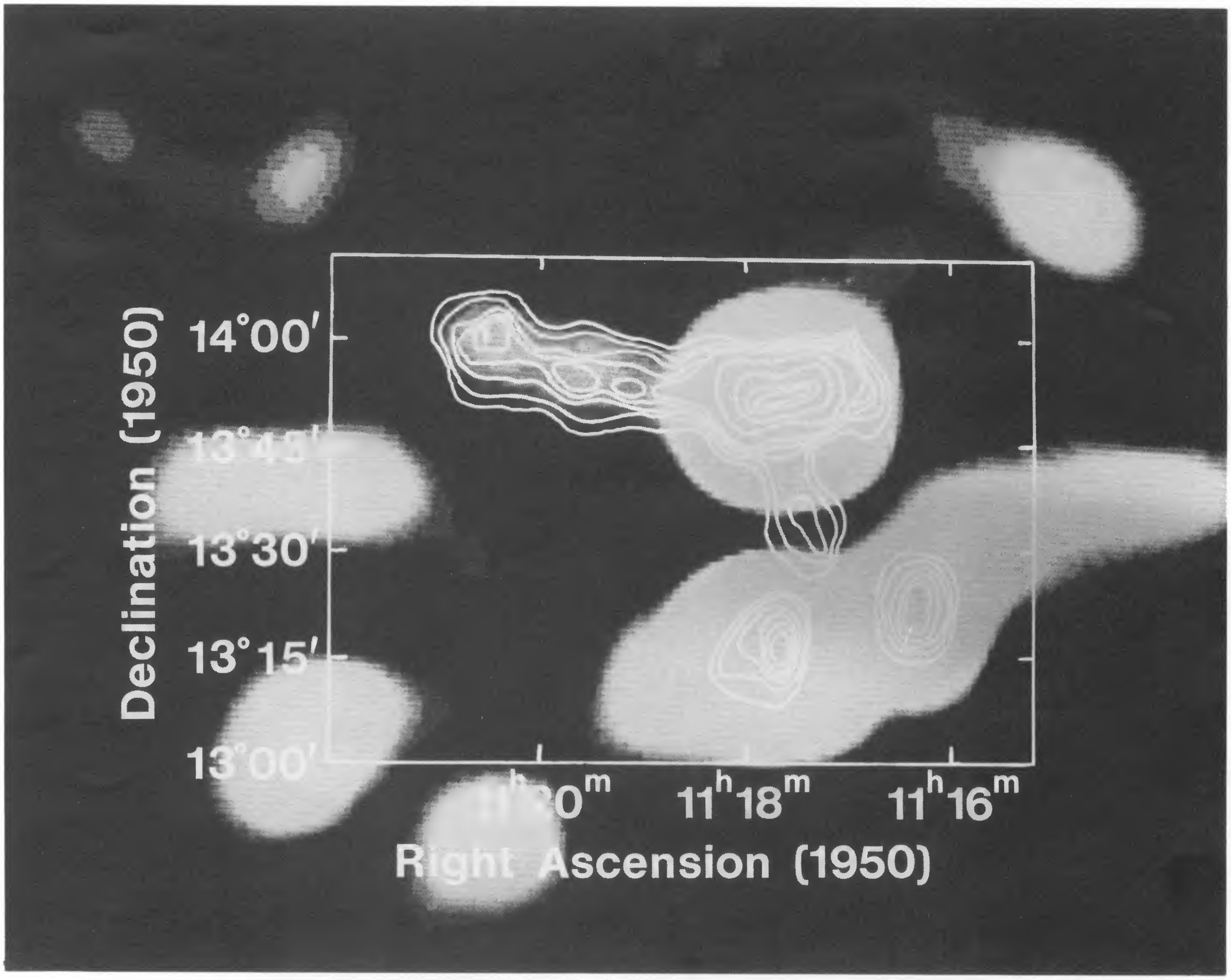

FIG. 5.—The integrated H I emission (contours) taken from the Arecibo observations of HGR superposed on the smoothed 100 μm *IRAS* image of the Leo triplet. New VLA observations (P. N. Appleton, in preparation) do not confirm the existence of the southern H I extension of NGC 3628 shown in the Arecibo data.

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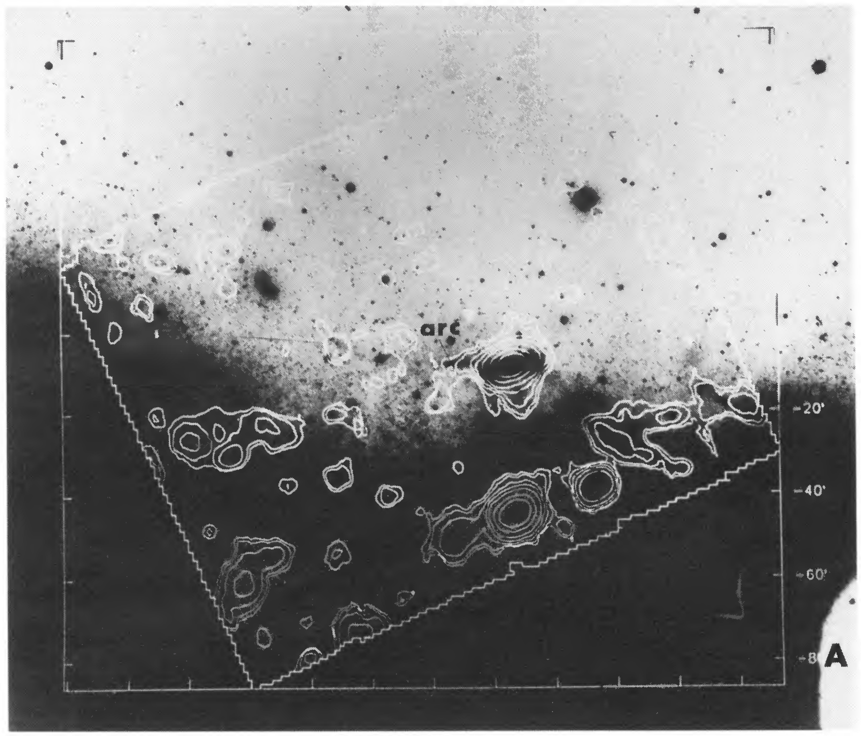

FIG. 6*a*

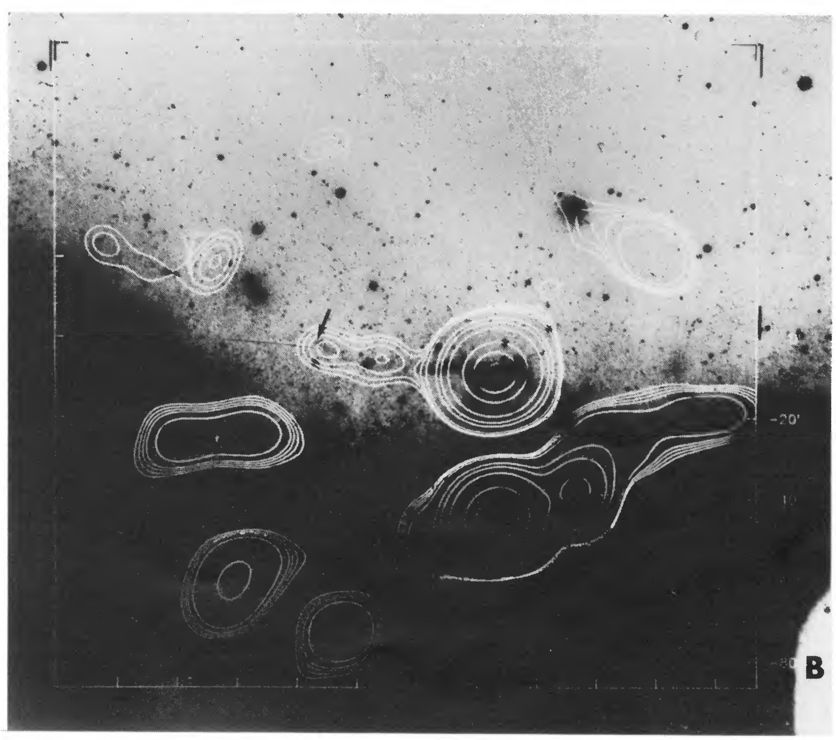

FIG. 6*b*

FIG. 6.—(*a*). Full resolution 100 μm *IRAS* emission (contours; see Fig. 3*b*) superposed on the SPSS plate of Fig. 2. Note the *IRAS* emission associated with the bright optical "arc" in the plume. (*b*) Contours of the smoothed 100 μm *IRAS* image superposed on the high-contrast copy of the SPSS plate. The arrow shows the tip of the optical plume associated with NGC 3628 (*center*).

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at a position consistent with the extension. We conclude that the 60 and 100 μm extension in this direction is probably a combination of both low level hysteresis and poor resolution of detected faint background sources and should not be treated as a positive correlation with the H I distribution. We note that the reality of the southern H I extension may in itself be in dispute, since recent VLA mapping (P. N. Appleton, in preparation) failed to detect the southern H I feature.

The optical emission and H I distribution of NGC 3627 are characteristic of a disturbed galaxy. Its 60 and 100 μm emission is somewhat extended. However, it is clear from Figures 3*a* and 3*b* that an additional source lies close to its eastern edge. This source is resolved into smaller knots at 60 μm. It is quite extended since it is present in the smoothed maps. Interestingly, the H I emission of HGR shows a similar extension to the east. However, unlike the case of the H I plume, its spatial distribution does not match that of the H I very well, and we cannot assume that it is associated with the Leo group. Its color temperature ($T = 26$ K for an assumed emissivity proportional to ν^1) offers no clue to its nature since its value lies within the range of possible values for both Galactic clouds and extragalactic sources. Until higher resolution observations are available, both in the infrared and radio, the possibility that the extension associated with NGC 3627 is extragalactic must be treated with caution.

4. PROPERTIES OF THE INTERGALACTIC PLUME

In Table 3 we present the 60 and 100 μm properties of the FIR plume along with optical and H I information. At 100 μm the plume has a total flux of 3.0 ± 0.5 Jy integrated down to the 1.5 σ level in the smoothed map. This corresponds to an intensity $I_{100\mu m}$ of 0.14 MJy sr^{-1}. Using the fluxes at 60 and 100 μm for the plume, the effective far-infrared luminosity, $L_{\rm FIR}$, is $1.1 \times 10^8\ L_\odot$. This is approximately 2% of the total IR luminosity of NGC 3628. We estimated in § 2 that the total optical luminosity, L_B, was $1.0 \times 10^9\ L_\odot$. The ratio $L_{\rm FIR}/L_B = 0.64$ is typical of that of spiral galaxies.

A second interesting property of the plume is the ratio of $I_{100\,\mu m}/N_{\rm H}$, where $N_{\rm H}$ is the H I column density. In the outer regions of the Galaxy, there is a good correlation between H I and IR cirrus. Typical values of $I_{100\,\mu m}/N_{\rm H}$ are 4.2 to 6.4×10^{-15} Jy sr^{-1}/(H I atoms cm^{-2}) (Terebey & Fich 1987). More recently, Boulanger & Perault (1988) have made a major study of diffuse Galactic emission and find values ranging from 5 to 24×10^{-15} Jy sr^{-1}/(H I atoms cm^{-2}). The higher values in this latter study appear related to an increase in the UV radiation field associated with star-forming regions. We evaluate the ratio $I_{100\,\mu m}/N_{\rm H}$ for the Leo plume in two ways. First, we calculate the ratio of the two FIR bright regions (X, Y) seen on the full-resolution map at 100 μm of Figure 3*b*. For the H I estimate, we use the data from HGR which were obtained with the Arecibo radio telescope which has a primary beam FWHM of 3'.3. These data are presented in HGR in a contour form in units of $\int T_a\, dV$, where T_a is the antenna temperature and V is the velocity in km s^{-1}. In order to convert to column density we multiplied these units by a factor of $1/\eta \times 1.83 \times 10^{18}$, where η of approximately 0.66. The peak H I column density at the position of both *IRAS* peaks are therefore calculated as 6.9×10^{19} atoms cm^{-2}. It is likely that these H I column densities are lower limits to the true column densities of the clouds since most H I cloud complexes in tidal filaments have physical scales of typically 1–10 kpc (see Sancisi 1981 and Appleton & van der Hulst 1988) which is smaller than the Arecibo resolution at the assumed distance of 6.25 Mpc. However for the evaluation of the $I_{100\,\mu m}/N_{\rm H}$ ratio all that is required is that the resolution of the radio telescope be similar to that of the *IRAS* observations (assuming that the dust and H I are homogeneously mixed). The HPBW of the point-spread function of the 100 μm measurements (4'.6 × 4'.2) is slightly larger than the radio resolution. We have therefore corrected the ratio by a factor of 1.8 (the ratio of the areas of the two beams) to derive the ratio of $I_{100\,\mu m}/N_{\rm H}$ for the two *IRAS* bright "hot spots" in the plume. These values are found to be 9.36×10^{-15} and 4.7×10^{-15} Jy sr^{-1}/(H I atoms cm^{-2}) for the tip and base of the plume, respectively. As a further check, we also estimated the intensity weighted average value of $N_{\rm H}$ over the entire H I plume and compared that with a similar average of the value of $I_{100\,\mu m}/N_{\rm H}$. We have assumed that the dust-to-gas ratio, the dust properties, and the radiation field are uniform across the projected beam areas. This ratio was found to be $7 \pm 4 \times 10^{-15}$ Jy ster^{-1}/(H I atoms cm^{-2}). In all cases the $I_{100\,\mu m}/N_{\rm H}$ ratio for the plume appears to be in striking agreement with that determined for diffuse cirrus clouds in our own Galaxy and we will argue that this is additional evidence for the extragalactic nature of the FIR plume.

We have also estimated the FIR color temperature of the plume. It is clear from Figures 4*a* and 4*b* that the plume is shorter at 60 μm than at 100 μm. We split the plume into two parts, east and west of R.A. (1950) 11$^{\rm h}$20$^{\rm m}$. Only the western (inner) half of the plume is detected at both 60 and 100 μm. The western half has a flux ratio $f(100)/f(60)$ of 2.74 ± 0.05 yielding a color temperature of 33 K. For the eastern half the failure to detect the end of the plume at an intensity level of 0.05 MJy sr^{-1} leads to an upper limit of $f(100)/f(60)$ of 3.78 or $T < 30$ K. Hence a temperature gradient is apparent along the length of the plume running from higher temperatures close to NGC 3628 to lower temperatures at the tip of the plume. This will be shown to be quite consistent with the tidal model of the plume formation process. We discuss the heating mechanism for the dust grains in a latter section.

In order to estimate the total mass of dust in the plume, we made some simplifying assumptions. Following Bode et al. (1988) and Hildebrand (1983), the mass of a single temperature dust component can be estimated from the 100 μm flux, $f_{100\,\mu m}$, using the expression

$$M_d = \frac{4}{3}\, a\rho\, \frac{f_{100\,\mu m}}{Q_\nu\, B_\nu(T)}\, D^2\ , \qquad (2)$$

where D is the distance to the dust cloud, a is the grain size, and ρ is the mass density of the grains. Adopting the expression for the absorption coefficient, $Q_{100\,\mu m} = 1.9 \times 10^{-4}$(a/0.01 μm), used by Bode et al. (1988), the mass can be found without specifying the grain size. We adopt values of $\rho = 2$ g cm^{-3}, a dust temperature in the plume of $T = 33$ K and a distance to the Leo group of 6.7 Mpc. The value of ρ we have assumed for the grains is typical of either carbon or silicate type grains in our own Galaxy, after taking into account the uncertainties in porosity of the grains (D. C. B. Whittet, personal communication), and is a major uncertainty in this calculation. We therefore estimate that the total mass of warm dust ($T > 21$ K) in the plume is $2 \times 10^4\ M_\odot$. Taking the total H I mass of the plume to be $9 \times 10^8\ M_\odot$ (Haynes, Giovanelli, & Roberts 1979) gives a dust-to-gas ratio, $M_d/M_{\rm H\,I}$ of 3.3×10^{-5}. This is significantly lower than the dust-to-gas ratio for the inner part of our own Galaxy, but it is only 30 times lower than that of the outer Galaxy (Sodroski et al. 1987). We will show that this apparent global underabundance of processed material is consistent with the tidal model for the formation of the Leo plume.

4.1. *Is the FIR Emission from the Plume Region Confusion with Foreground Galactic Cirrus?*

It is clear that after subtracting the background Zwicky galaxies there remain unidentified 100 micron sources in the smoothed map of Figure 4*b*. A critical question in the interpretation of the faint FIR emission from the direction of the H I plume is whether the emission is (*a*) truly extragalactic or (*b*) that it is the chance alignment of local cirrus with the background Leo group. A similar problem was addressed by Abolins & Rice (1987) who investigated a region in the vicinity of the "Arp ring" near M81. They concluded that the distribution and color temperature of the possible extragalactic emission was more consistent with Galactic dust which is found in profusion in the M81 region. However, the case of emission in the Leo triplet of galaxies is somewhat different. The remarkable correspondence in the region of the optical plume between the 100 and 60 μm emission and the H I distribution, both in its length and orientation, strongly suggests that this FIR feature is a true extragalactic counterpart to the tidal filament associated with NGC 3628. This is supported by the higher than normal color temperature of 33 K for the inner plume compared with values of $T < 30$ K typical of Galactic cirrus clouds. For comparison, the other extended regions in the Leo field which are not identified with galaxies are more likely to be Galactic cirrus features. The plume feature stands out as being the only extended emission region with $T > 30$ K. This fact alone, however, is not conclusive proof of an extragalactic origin for the FIR emission since equally high temperature regions are known in our own galaxy (see Boulanger & Perault 1988), although they are usually associated with major star-forming complexes. Further support for the plume being extragalactic comes from the ratio of $I_{100\,\mu\mathrm{m}}/N_{\mathrm{H}}$ in the plume. This value is very similar to that determined in Galactic clouds even though the H I column densities are obtained from redshifted H I emission clearly associated with the Leo group. We believe that the above factors taken together are very unlikely to occur by chance, and so we assume that the *IRAS* plume is extragalactic. The very large angular extent of the plume (45′) has probably contributed to its detection with *IRAS*.

5. DISCUSSION

It can be seen from Table 3 that the ratios of L_{FIR}/L_B and the color temperatures of NGC 3628 and NGC 3627 are very typical of normal galaxies. Both galaxies lie close to the mean in the distribution of L_{FIR}/L_B versus 60/100 μm color temperature obtained by Bothun, Lonsdale, & Rice (1989) for the UGC sample of optically selected spiral galaxies. On the other hand, NGC 3623 lies at the extreme low end of the range of L_{FIR}/L_B for the UGC sample and has a somewhat lower 60/100 μm color temperature than the majority of galaxies in that sample. This low level of FIR activity for an Sa type galaxy is to be expected since the galaxy has a low H I mass to luminosity ratio ($M_{\mathrm{H}}/L_B = 0.02$) and was not detected in a recent CO molecular search of the galaxy by Young, Tacconi, & Scoville (1983). Hence, it would appear that little active star formation is occurring in NGC 3623 at the present epoch. This inactivity, combined with its lack of optical peculiarities confirms the view of Rots (1978) that NGC 3623 plays no major part in the formation of the H I plume by tidal interaction with its companions.

The detection of FIR emission from the Leo plume shows for the first time direct evidence for the existence of dust in the intergalactic environment. The observations provide strong evidence that H I plumes like Leo (see, for example, Sancisi 1981; Haynes, Giovanelli, & Chincarini 1984; Appleton & van der Hulst 1988) are not pure H I/He primordial clouds but contain processed material. A natural explanation for the origin of dust is via low-level star formation in the outer regions of NGC 3628 before and during the tidal stripping of the outer regions of this galaxy by NGC 3627.

In the model by Rots (1978) and unpublished models by A. Toomre, the H I and stellar plume appears as a one-armed spiral structure if viewed from above the plane of the high inclination orbit of NGC 3627 about NGC 3628. However, when viewed edge-on this extended spiral feature appears compressed into a linear filament. On the basis of both the size of the plume and the mass of NGC 3628, Rots estimated the age of the plume to be 10^9 yr old. The optical and infrared data provide clues in determining the star formation history of the gas in the plume over this relatively long period of time. If we accept the tidal explanation as a working hypothesis for the origin of the plume, we can then consider the nature of the heating source for the dust in the plume. From the CCD observations we estimated the total optical luminosity for the plume as a whole and found that the $L_{\mathrm{FIR}}/L_B = 0.64 \pm 0.05$. This is well within the range obtained for normal galaxies (Bothun, Lonsdale, & Rice 1989) suggesting a similar heating mechanism for the dust in spiral disks. The FIR data suggest that the brightness temperature of the dust is lower in the outer half of the plume, $T < 30$ K, compared with the value of 33 K nearer to NGC 3628. This apparently follows the overall trend of the optical surface brightness with fainter emission in the outer part of the plume compared with that closer to the galaxy. In contrast to this, the H I surface density and the 100 μm IR intensity does not fall off along the plume. There is also a close spatial correspondence in the plume of the brightest 100 μm emission with the optical "arc" suggesting that in regions where the optical emission is enhanced in brightness, so too is the IR emission. The most obvious heating source is therefore stars embedded in the plume.

The apparently lower color temperature of the outer plume can be understood in terms of a dilution of the stellar optical and UV radiation field with distance from NGC 3628. If the dust is distributed homogeneously with the H I gas, then the decrease in temperature can be explained as either (*a*) a decrease in the number of hot blue stars or (*b*) a general decrease in the space density of stars, both as a function of distance along the plume. In case (*a*), one would expect to see an optical color gradient along the plume which is not observed. Although some regions of the plume are bluer than their surroundings (see § 2) there is no noticeable radial trend. The case for (*b*) is stronger. Both the proposed tidal model of Rots (1978) and observations of large-scale spiral arms in galaxies (e.g., M101, M51) show a tendency for the stellar density in the arm to decrease away from the galaxy. This is supported by the deep plate material for the Leo plume which shows that the average optical surface density of the outer plume is significantly lower than that of the inner plume. It would be natural that a dilution of the stellar radiation field would be expected to lead to a lowering of the FIR color temperature in the outer plume, as inferred from our observations.

The fact the H I and 100 μm surface densities do not decline in the outer plume is perhaps surprising, given the change in the optical surface brightness here. New VLA observations of the H I by P. N. Appleton, (in preparation) show that the surface density is actually higher at the end of the plume where it curls around on itself. Overall, then the 100 μm emission appears to follow quite closely the H I surface density, while only the color temperature of the dust responds to the change in optical brightness.

We indicated earlier the dust-to-gas ratio in the plume is approximately 30 times lower than that obtained for the outer region of our Galaxy. This is not inconsistent with the interaction model which requires that the plume is primarily material tidally stripped from the outer regions of NGC 3628, which are unlikely to have undergone much star formation prior to the interaction. However, since the time of the initial tidal perturbation, star formation has apparently still continued after the gas and stars were pulled from NGC 3628. Evidence for this comes from relatively blue knots ($B-V = 0.5$–0.8), seen in the optical CCD data. Such colors are normally associated with young (O/B/A) stars which have main-sequence lifetimes shorter than the age of the plume (estimated by Rots to be $T \leq 10^9$ yr). We are forced to conclude that recent star formation has taken place, a conclusion supported by other studies of tidal plumes (Schombert, Wallin, & Struck-Marcell 1990).

A second possibile explanation for the low dust-to-gas ratio in the plume is that the dust and gas have very different filling factors. A single CO observation of the plume was made at the H I peak by Young, Tacconi, & Scoville (1983). No molecular gas emission was detected in contrast to the strong CO emission from NGC 3627 and NGC 3628 suggesting that at that position, at least, no giant clump of molecular material exists. We cannot rule out the possibility of differing spatial distributions until higher angular resolution data are available in the IR and more extensive CO observations are made of the plume.

6. CONCLUSIONS

We have obtained *IRAS* CRDD, CCD data, and new optical plate material on the Leo triplet of galaxies. We report the discovery of a faint FIR counterpart to the giant H I and optical plume associated with NGC 3628. The plume which is 45′ in length is detected most strongly at 100 μm and has the same dimension and orientation as the extragalactic plume. The inner part of the plume is detected also at 60 μm. We believe the FIR plume is extragalactic and not local Galactic cirrus.

Working on the assumption that the FIR emission is associated with the plume and drawing on new optical data we conclude that (*a*) the present observations represent the first extragalactic discovery of all major components of a galaxy in a tidally induced filament, namely, gas, stars, and dust (*b*) the Leo plume has a dust-to-gas ratio of 3.3×10^{-5}, a factor of 30 times lower than the outer Galactic anticenter region. This is consistent with the tidal model of Rots (1978) for the formation of the H I/optical plume in which the plume is tidally stripped from NGC 3628 by an interaction with NGC 3627. The very outer regions of NGC 3628 would have experienced very little chemical evolution over a Hubble time and would be deficient in dust; and (*c*) the FIR and optical data are consistent with a picture in which a relatively young population of stars distributed throughout the H I plume heats the dust. The apparently cooler IR color temperature of the outer plume compared with the inner plume is probably the result of the dilution of stellar space density along the plume.

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