Final Report for: **The Relation between FIR and**

**H I Emission in Galaxies**

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Report Date: December 27, 1991

JPL Contract No: 958347

## ABSTRACT

This project explored the relationship between the global far-infrared and neutral hydrogen (H I) emission from galaxies, based on data from the Infrared Astronomical Satellite (IRAS) and published radio data. $100\mu m$ and $60\mu m$ IRAS fluxes were used to establish a temperature-corrected measure of the cold dust emission, and H I fluxes were drawn from the literature with the greatest possible consistency. The degree of correlation between the FIR and H I fluxes was found to be better than in previous studies, comparable to the correlation previously found between FIR and CO fluxes. The improvement was obtained largely by (1) separating "stripped" from "unstripped" galaxies, and (2) using compatible sources of H I data. Stripping occurs in clusters of galaxies and is probably caused by ram-pressure effects as a galaxy travels through the intergalactic medium. Our results suggest that stripped galaxies have had their outer-disk gas removed ($\sim$80% of their total H I) while retaining most of their $100\mu m$-emitting dust. This strongly shifts the ratio of their $100\mu m$-to-H I fluxes. The second problem, arising from diverse sources of data, arises because differing telescopes and observational techniques give rise to substantial disagreement in the measured H I flux, and this degrades the correlation of the FIR and H I fluxes.

## 1. Introduction

This project explored the relationship between far infrared (FIR) and 21 cm atomic hydrogen (H I) emission in galaxies. The primary goals were to determine to what degree any correlation between the two fluxes could be used to understand the likely location of FIR-emitting dust within galaxies, and to see how variations in the relative fluxes might be related to environmental influences. In addition, it was our hope to expand the the pool of useful H I data in the literature to allow the extension of FIR/H I comparisons to larger samples.

Past efforts to find a correlation between the global atomic neutral hydrogen (H I) content and the far infrared (FIR) emission in galaxies yielded conflicting results. Different studies found a non-existent (Leggett, Brand, and Mountain 1987), a weak (Knapp, Helou, and Stark 1987), or a strong (Hutchings 1989) link between the two quantities. By comparison, the correlation between the molecular gas content (based on the CO luminosity) and the FIR emission has been well established (Young *et al.* 1989). In this project we used *Infrared Astronomical Satellite* (IRAS) measurements to show that the inconsistency of the earlier studies was largely a consequence of H I stripping, and conversely we found that comparisons of H I and FIR emission provide a good measure of H I stripping.

Among normal isolated spiral galaxies, the H I vs. FIR properties prove to occupy a fairly narrow range, with dispersions comparable to those found for the CO-to-FIR ratio. Mildly interacting galaxies with higher levels of star-forming and consequently increased FIR emission have essentially the same ratio of H I-to-FIR emission once the FIR measurements are temperature-adjusted, and we show that this conclusion is independent of the emissivity index chosen. On the other hand, galaxies which have suffered gas stripping in dense clusters exhibit greatly reduced H I levels relative to the FIR emission, so that the H I-to-FIR ratio might be used as a stripping indicator.

The results of this research have been presented by Spitzak and Schneider (1990, 1992), and are part of the Ph.D. dissertation of Spitzak (in preparation).

## 2. Data Analysis

### 2.1 The H I/100μm Index

In this study, we took exception to the standard practice of comparing luminosities, to avoid distance-dependent measures which may give rise to false correlations. Even if the distances were well-known, some part of any correlation found between two luminosities (or any other extensible measures) of a galaxy will arise for no other reason than bigger galaxies should produce more emission at all wavelengths. We also avoided using highly model-dependent dust masses since they depend on uncertain extrapolations.

To examine the relationship between neutral hydrogen and far-infrared emission, we define an "H I/100μm index" as the ratio:

$$Index = \log\left[\left(\frac{\int S_{\mathrm{H\,I}}\,dv}{\mathrm{Jy\ km\,s^{-1}}}\right)\bigg/\left(\frac{F_{100\mu m}}{\mathrm{Jy}}\right)\right]$$

where $F_{100\mu m}$ has been "temperature-adjusted" (see below). This particular distance-independent ratio was chosen since it showed a smaller scatter than H I-to-60μm or H I-to-"total" (60μm plus 100μm) FIR flux ratios. The improvement from using 100μm fluxes is most likely a consequence of this wavelength being nearer to the peak of the emission from the dominant population of large dust grains. The 60μm flux is more influenced by stochastic heating of small grains (Draine and Anderson 1985; Boulanger *et al.* 1988).

It is important to consider dust temperature in examining FIR fluxes, since the same quantity of dust will produce different fluxes as $T^{4-5}$. To adjust the emission, $f_\nu(T)$, we determined the temperature that best matched the observed 60μm-to-100μm emission ratio:

$$F_{60\mu}/F_{100\mu} = \int f_\nu(T) R_{60\mu}\,d\nu \bigg/ \int f_\nu(T) R_{100\mu}\,d\nu \ ,$$

where $R_{60\mu}$ and $R_{100\mu}$ are the relative system frequency-responses of the detectors over their respective wavelength bands (Beichman *et al.* 1988). Given the derived temperature for this emission curve, we estimated the increase in 100μm emission due to increased temperature. Such an adjustment is obviously dependent on the form of the emission curve assumed, but the *relative* adjustment for different galaxies

proves to be quite insensitive to the choice of models. For example, although there was a great deal of variation in the derived temperatures for one warmer-than-average galaxy when we assumed emissivity indices of:

$$0.500 \qquad 1.750 \qquad 3.000,$$

the 100$\mu$m enhancements determined relative to the average galaxy were almost identical at:

$$1.566 \qquad 1.573 \qquad 1.592.$$

Thus, the detailed properties of the dust—the particle size distribution, its composition, etc.—should not affect the temperature-adjusted 100$\mu$m flux, so long as the properties are similar from galaxy to galaxy. The particular model is not critical to our analysis, but for purposes of comparison we chose a black body curve modified by an emissivity index of 1.5 (which lies between the indices for optical and extreme-infrared dust properties), and with this model we found that isolated "normal" galaxies typically have mean dust temperatures of 30 K, which we adopt as our fiducial model.

## 2.2 The HI Data

In any comparison of HI and FIR fluxes, it is essential that the inconsistencies between methods of measurement not be permitted to spoil the relationship. Data from IRAS is essentially uniform, but when using HI fluxes from the literature, there are systematic errors that can creep in, since a wide variety of numbers have been published under the heading of "integrated HI flux." Single beam measurements at the centers of galaxies miss different amounts of flux depending on the beam size; some authors have published raw values, and others have used a variety of algorithms to correct for beam size. Other galaxies have been mapped at several points, usually along the major axis, and an even wider variety of models have been developed to combine these measurements to derive global fluxes. Synthesis array fluxes have a systematic bias in that they apply a spatial frequency cut off and can effectively "resolve out" some of the HI flux. In addition, there are confusion and pointing errors, and occasionally systematic differences in calibration techniques and self-absorption corrections applied.

The best correlations are found when samples were limited to the narrowest range of HI measurements: those made with the same telescope, by the same observer, using the same reduction method. Thus, although Young *et al.* (1989) found that the mean scatter in the HI-to-FIR ratios among their galaxy sample was larger than for their CO data, they used HI data from a wide variety of sources, whereas the CO data had been obtained and reduced uniformly. We note that the distribution of the CO-100$\mu$m log flux ratio (calculated in the same way as the HI/100$\mu$m index) in the data of Young *et al.* has a standard deviation of 0.37, compared to 0.55 for their HI data. However, when we chose a sample of isolated galaxies restricted to HI detections recorded in a single paper, we found a standard deviation in the HI/100$\mu$m index of 0.37—just as good as for CO.

We stress that comparisons based on HI data from different sources may have significantly larger errors than comparisons of data for different subsamples of galaxies from a single source. We attempt to avoid such problems by concentrating on a single source of HI data at a time, complementing it with others' measurements only when necessary to complete a galaxy sample or resolve issues of confusion.

Unfortunately, combining data from various sources to make a much larger database is generally counter-productive. The problems of combining datasets were compounded by the fact that many of the large studies were based on samples chosen according to criteria which interfered with our own selection criteria; thus, for example, it becomes difficult to disentangle the effects due to morphological differences between galaxies when the HI data came from different observers' samples which were themselves selected by morphological type. We spent a considerable effort attempting to produce consistent datasets which bridged the differences between samples, but the differences in techniques and telescopes increased the scatter to the degree that better results were obtained asking specific questions of more-restricted samples. This limited our ability to carry out a more generalized principal component analysis.

## 2.3 The FIR Data

The FIR data was drawn primarily from the Faint Source Survey (FSS) database (Moshir *et al.* 1989). We tested a subset of those data relative to ADDSCAN measurements to determine their accuracy and found that the FSS values were consistent for smaller galaxies. The IRAS 100$\mu$m scan detector size is $\sim 5' \times 3'$, We found that differences in the derived fluxes compared to ADDSCAN fluxes only became significant for galaxies with optical diameters larger than 5'; galaxies between 4' and 5'

show marginally lower FSS than ADDSCAN fluxes, although not at a statistically significant level. We restricted consideration to galaxies smaller than $5'$. FSS fluxes are in good agreement with those obtained from coaddition: we found for a sample of 84 small (¡ $4'$) galaxies the FSS $100\mu$m fluxes agreed to 1% in the mean.

We obtained FSS data at the positions of all published H I-detected galaxies as well as a sample of undetected galaxies in order to compare the detection rates, and we found the effective detection limits for $100\mu$m detections with IRAS were very similar to the H I detection limit using the Green Bank 91 m telescope. For example, in a sample of galaxies selected by Davis and Seaquist (1983), 183 of 213 galaxies were detected at H I, $60\mu$m, and $100\mu$m. Of the remaining galaxies, 17 were detected at none of the wavelengths, while 8 had an upper limit on the FIR emission and 5 on the H I Moreover, only one of the partially-detected galaxies proved to have an "interesting" H I/$100\mu$m index, in the sense that the limit would imply a value more than $1\sigma$ outside of the central range for the detected galaxies. We therefore conclude that the undetected galaxies do not indicate any significant differences from the results based on the detected galaxies.

## 3.   The H I/$100\mu$m Index for Normal Galaxies

Both isolated and mildly interacting galaxies yield the same value for the H I/$100\mu$m index. Samples of isolated galaxies are used to arrive at a standard fiducial value of $\sim$0.50, which is consistent to within about 0.10 even when different reduction procedures for the H I measurements have been used.

We examined two isolated-galaxy samples to derive a fiducial value for the H I/$100\mu$m index. The first isolated sample is based primarily on the Green Bank H I data of Davis and Seaquist (1983). We find a mean value for the H I/$100\mu$m index of $0.52 \pm 0.05$ (error in the mean). Combined with the similar inaccuracy of the FIR measurements, these errors would contribute a spread in the H I/$100\mu$m index of about 0.15. A second sample of isolated galaxies observed in H I by Haynes and Giovanelli (1984). This set of galaxies had smaller angular diameters on average, the H I measurements were made at the Arecibo 305 m telescope, and the H I fluxes were calibrated using different procedures. The isolated galaxies in this second sample yielded a mean H I/$100\mu$m index of $0.45 \pm 0.04$.

The sense of the differences between the two measurements of the mean H I/$100\mu$m index is the same as that of the relative beam-sizes of the different telescopes used. There may be some undetected outer H I associated with some of the larger galaxies observed with the smaller Arecibo beamsize (HPBW $\sim 3'.3$) which might account for the lower mean value. There may also be a slight bias in the opposite direction for the first sample, in that the Green Bank beamsize (HPBW $\sim 10'$) is larger than the $100\mu$m detector area, so the larger galaxies could have slightly underestimated FIR fluxes. We adopt an intermediate value of 0.50 for the fiducial value of the H I/$100\mu$m index.

In comparison to isolated galaxies, the members of interacting systems show higher FIR fluxes, but assuming this is primarily a heating effect, it should not alter the overall gas-to-dust ratio or temperature-adjusted H I/$100\mu$m index. This is confirmed by the Davis and Seaquist (1983) sample of interacting galaxies, again using Green Bank H I observations. Collectively this sample showed a warmer mean FIR color of $\log(F_{60\mu m}/F_{100\mu m}) = -0.333 \pm 0.016$, compared to $-0.452 \pm 0.015$ for the isolated sample. The interacting sample also yields a mean H I/$100\mu$m index $0.25 \pm 0.07$ lower than for the isolated galaxies before making any temperature adjustments. The temperature enhancement of the $100\mu$m emission explains this difference without requiring any difference in the mean atomic gas-to-dust ratio. After temperature-adjusting each galaxy to 30 K, as explained above, the two samples yielded mean H I/$100\mu$m indices differing by only $0.05 \pm 0.07$ from each other. This indicates that the relative amount of atomic gas and $100\mu$m-emitting dust is basically the same in the two samples, and that the temperature-adjusted H I/$100\mu$m as a reasonable estimator of the atomic gas-to-dust ratio, at least for galaxies without exceptionally high FIR dust temperatures.

## 4.   The H I/$100\mu$m Index for Cluster Galaxies

In contrast to the isolated and interacting galaxies, we found that the H I/$100\mu$m index of galaxies can be strongly affected by the environment inside clusters. Cluster galaxies divided into two distinct groups which corresponded to those whose H I is stripped or unstripped. The unstripped galaxies agree well with the fiducial value of the H I/$100\mu$m index, but the stripped galaxies exhibit a much lower value of

the index, implying a level of H I lower by a factor of $\sim$5 relative to the dust emission. This is reasonable for a standard model of $100\mu$m emission produced primarily in the inner disk of galaxies since the stripping process removes material from the outer disk first. It also explains the poor correlation between H I and $100\mu$m emission found for cluster spirals by Knapp *et al.* (1987).

We examined two samples of cluster galaxies, a nearby set in the Virgo Cluster and a compilation of data for galaxies in several more-distant clusters, in order to determine how the H I/$100\mu$m index was affected by H I stripping. The Virgo sample was observed by Knapp *et al.* (1987), and coadded FIR and H I data were used for these large-angular-diameter galaxies. To more-distant cluster data were drawn from Bicay and Giovanelli (1987). These data are neither as complete, nor of as high signal-to-noise as the Virgo data, but they provided a useful comparison.

We subdivide the cluster galaxies according to whether their neutral hydrogen content appears normal. Haynes and Giovanelli (1984) define an H I deficiency index in terms of the difference between the observed H I mass and that expected for an isolated galaxy of the same optical linear diameter $D_L$ and morphological type $t$ as:

$$Def = \log\left[M_{\mathrm{H\,I}}(t, D_L)\right] - log\left[M_{\mathrm{H\,I}}(obs)\right] .$$

Since it is based on optical diameters at low surface brightness and subjective morphological types, the determination of H I deficiency is somewhat uncertain, but it provides a useful starting point. As our "stripped" sample, we chose galaxies with H I deficiencies greater than a factor of 2 (i.e. $Def > 0.30$) according to this optical criterion. The H I/$100\mu$m index was clearly distinct for stripped and unstripped galaxies. The unstripped galaxies have a mean value of the index of $0.45 \pm 0.08$, in excellent agreement with the fiducial value for isolated galaxies, but the stripped galaxies yield a much lower mean index of $-0.21 \pm 0.06$. This implies that, relative to the $100\mu$m emitting dust, on average there is 4.6 times less atomic hydrogen present in the stripped galaxies.

The galaxies can be well-separated into stripped or unstripped categories based on whether their H I/$100\mu$m index is less or greater than 0.2. Using that criterion misidentifies only 30 of 169 galaxies as belonging to the wrong category according to the Haynes and Giovanelli (1984) definition. This is excellent agreement given that their method depends the uncertain measurement of $D_L$ at various inclinations and the difficult determination of morphological type for galaxies with small angular diameters or large inclinations. Thus, the H I/$100\mu$m index appears to be as good an indicator of stripping as the $Def$ measure. The H I/$100\mu$m index also has the advantage that it is based on two global flux measurements with relatively straightforward interpretations, and in tests of the temperature properties of stripped and unstripped galaxies, the H I/$100\mu$m index yielded smaller dispersions than the deficiency index.

One intriguing possibility is suggested by the bimodality of the H I/$100\mu$m index for the best-measured cluster galaxies. It implies that H I stripping is an all-or-nothing process, occurring over relatively short timescales.

Another surprising result is that the dust remaining in the stripped galaxies is on average cooler than in the unstripped galaxies, whereas according to the standard picture it would be expected that stripping material from the presumably cold outer disk would leave behind primarily warmer dust. Combining the results for the two cluster samples and using the H I/$100\mu$m index to determine which galaxies are stripped, we found a FIR color index lower by $0.061 \pm 0.021$. Thus, we formally find that the stripped sample is drawn from a lower temperature population of galaxies at a 99.6% level of confidence.

This small difference is of sufficient significance to warrant examining its possible implications for understanding the stripping process and possible dust-distribution models. A lowered mean temperature suggests already that the stripping is *not* caused by conductive heating of a galaxy's interstellar medium by the intra-cluster gas, which would presumably raise the mean temperature of the remaining material. It does suggest that ram-pressure sweeping must remove warmer than average dust which is presumably associated with the diffuse H I gas in the inner disk of the galaxies.

## 5. Summary

We find the H I/$100\mu$m index to be a useful indicator of changes in the amount of atomic gas relative to the amount of $100\mu$m emitting dust. Normal galaxies display a fairly narrow range in the the value of the index, centered at a value of 0.5 (which assumes a mean dust temperature of 30 K and an emissivity index of 1.5). Galaxies in interacting systems display the same value of the H I/$100\mu$m index

once a temperature adjustment is made based on the the FIR color index. Thus we find that the atomic gas-to-dust properties are not altered by tidal interactions.

Interestingly, although we assume a particular model for the dust emission, we find this assumption has a negligible effect on the calculation of the HI/100$\mu$m index. Thus the result is essentially independent of the dust grain properties, so long as the dust grain properties do not change between samples of galaxies. This is a useful feature, as it allows us to adjust the HI/100$\mu$m index based on FIR color index without worrying about detailed dust models.

The HI/100$\mu$m index demonstrates the potential for being a good indicator of galaxies which have suffered HI stripping. Stripped galaxies in clusters identified by HI and optical criteria are found to have lost ~85% of their HI relative to the amount of 100$\mu$m emitting dust. The HI/100$\mu$m data in the Virgo cluster are also suggestive of a bimodal distribution, perhaps implying that HI stripping is an all-or-nothing process. A stripping criterion based on an HI/100$\mu$m index < 0.2 provides excellent agreement with the Haynes and Giovanelli (1984) deficiency index. We suggest that the HI/100$\mu$m index may prove to be a more useful indicator of HI stripping because, unlike the deficiency index, it requires no information about galaxy morphology or inclination, and because it has a relatively simple physical interpretation.

The similarity of our fiducial value of 0.5 for the HI/100$\mu$m index to that of 0.53 found for the diffuse infrared cirrus observed locally (Boulanger, Baud, and Albada 1985) might appear to suggest that the infrared emission in normal galaxies is dominated by FIR cirrus. This runs counter to the model of Devereux and Young (1990) that the FIR emission in galaxies is dominated by dust surrounding massive young stars, which would imply that the HI/100$\mu$m index for the cirrus should be much higher in a global average, since the cirrus would contain none of the significant infrared emitters. However, the results for stripped galaxies do not appear entirely consistent with either model.

Stripped galaxies provide us with the opportunity to determine, by their absence, the FIR properties of dust associated with the diffuse HI. It is clear that the 100$\mu$m-emitting dust cannot be primarily associated with the diffuse atomic gas since despite the dramatic loss of HI, there is not a corresponding large drop in the 100$\mu$m emission. Likewise, a lower color temperature in stripped galaxies implies that cooler dust is on average associated with the remaining dense regions. Of course, any model of the global FIR emission is complicated by the problem that we are not dealing with a single temperature blackbody emitter, but many dust components with various temperatures. Moreover, higher temperatures in a small fraction of the dust can dominate a color temperature calculation.

The large drop in the HI/100$\mu$m index observed in stripped galaxies can be understood if there is either very little dust in the diffuse outer disk, or if the dust linked with the HI outside of the optical disk is so cold that it is essentially invisible to even 100$\mu$m observations. Thus in removing the bulk of the HI from these outer regions, little change is produced in the global 100$\mu$m fluxes or the FIR colors. At the same time, ram-pressure sweeping may remove warm dust associated with diffuse atomic gas between dense, cold clouds within the optically bright portion of the disk, thus perhaps lowering the FIR colors slightly. The lower average dust temperatures in stripped galaxies may therefore indicate that a small, but significant fraction of the energy emitted at 100$\mu$m originates in this warm diffuse dust, while on average the dust associated with the remaining dense clouds is cooler.

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