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SPATIAL DECONVOLUTION OF IRAS GALAXIES AT 60 UM

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ABSTRACT

Using IRAS in a "slow scan" observing mode to increase the spatial sampling rate and a deconvolution analysis to increase the spatial resolution, several bright galaxies have been resolved at 60 um. Preliminary results for M 82, NGC 1068, NGC 3079 and NGC 2623 show partially resolved nuclei in the range 10 to 26 arcsec., full width at half maximum, and extended emission from 30 to 90 arcsec. from the center. In addition, the interacting system, Arp 82, along with Mark. 231 and Arp 220 were studied using the program "ADDSCAN" to average all available survey mode observations. The Arp 82 system is well resolved after deconvolution and its brighter component is extended; the two most luminous objects are not resolved with an upper limit of 15 arcsec. for Arp 220.

INTRODUCTION

In the design of the IRAS survey array the requirement for the highest possible spatial resolution was sacrificed in order to achieve wavelength and area coverage. However, a special observing mode was devised to utilize the best detector in each band coupled with the excellent pointing performance of the space craft to recover some of the lost resolution for bright sources. Unfortunately, only a few observations were obtained this way but most of those results are now available in preliminary form and are reported here since they provide important information on the size, structure and surface brightness of several bright infrared galaxies. It is also shown that many more results on the sizes and structures of extragalactic systems, especially those that are interacting, may be obtained by using a special method of processing for the survey data. After properly combining all available survey mode scans, each of which is under sampled, it is possible to recover enough information to construct a properly sampled scan of an object so that the powerful techniques of spatial deconvolution may be applied. This report includes very preliminary but interesting data obtained by this method and suggests that it should be applied to a much larger sample of galaxies.

THE "SLOW SCAN" PROGRAM

In order to deconvolve scans of bright objects to produce one dimensional images with resolution near the ultimate limit of the telescope system, three conditions must be met. First, the stability and reproducibility of the modulation transfer function, MTF, must be assured and it must be accurately measured using known point sources. Obviously, the MTF, or the point spread function, PSF, as it is often termed, should be fully optimized but this was not the case with IRAS for reasons explained above. Even though the IRAS detectors were too broad for best performance, if the second requirement of adequate sampling in the spatial domain were met, it should be possible to perform the deconvolution with success. This was accomplished for a limited set of observations by slowing the scan rate to one eighth of the normal survey rate, hence the name "slow scan". It was not possible to alter the set sampling rate in the time domain. Fortunately, the redundant observations which make up the vast body of survey mode data offer another viable solution to this under sampling problem and that approach will be discussed below. The third requirement for successful deconvolution is that of high signal/noise, thus, only bright sources were included.

TABLE 1. SLOW SCAN PROGRAM OBJECTS

GALAXIES		STARS	POINT SOURCES
M 82	STAR BURST	alpha Lyr	alpha Boo
N 1068	SEYFERT	alpha PsA	beta Gru
N 2623	INTERACTING	beta Pic	Hygia
N 2992	INTERACTING		
N 3079	INTERACTING		

Table 1 lists the complete set of "slow scan" sources and Table 2 summarizes the relevant parameters of IRAS. The choice of extragalactic objects for this program was dictated by an interest in the size and structural features of the brightest infrared galaxies and by the idea that it should be possible to resolve a number of interacting systems and, thereby, shed light on the mechanism of the interaction as it promotes excess infrared emission. During the mission the Vega phenomenon was discovered, Aumann et al (1984), and Fred Gillett wisely included the brightest objects of that class in this program. At this time only the 60 um observations of galaxies will be discussed in more detail.

TABLE 2. IRAS PARAMETERS FOR DIFFERENT MODES OF OBSERVATION

L	L/D	DET. WIDTH	SAMPLING INTERVAL SURVEY	STD. AO	SPE. AO	SLOW SCAN
(um)	(sec)	(sec)	(sec)	(sec)	(sec)	(sec)
12	4.3	45	14.4	7.2	3.6	1.8
25	8.9	45	14.4	7.2	3.6	1.8
60	21	90	29	14.4	7.3	3.6
100	35	180	58	29	14.4	7.3

Note: Detector lengths vary from 4.5 to 5 arcmin.

These observations consist of scans a few arcmin. in length which were repeated either 6 or 9 times by reversing the satellites' motion. In each band the best behaved detector in that band was used. It was found that non-linear and time dependent effects were present in the IRAS detectors which limited their performance in this application by more than the usual problem of signal/noise. For example, there are asymmetries in the scans which depend on the scan direction. By averaging the scans in both directions these effects largely cancel. It also is likely that "hysteresis" effects are present to some degree and serve as a degradation in the reproducibility of the MTF. The PSF also varies from detector to detector and as a function of cross-scan position for each detector. Normally each observation set was repeated at least once, providing both an opportunity to check for reproducibility and a second set of data to average. Thus the minimum number of scans averaged for a single object was 6 and the maximum was 12. The raw data were position reconstructed at JPL by a process which effectively gives 1 arcsec pointing accuracy for these measurements, and they were then uniformly re-sampled at 2 arcsec. intervals. After baseline subtraction the scans were normalized to their peak values and they were aligned for coadding using the midpoints between their half amplitudes. After averaging all the scans from an observation, they were resampled at 6 arcsec. intervals before further analysis.

DECONVOLUTION TECHNIQUES

When the 60 um IRAS detector, of dimensions 1.5 arcmin by 4.7 arcmin, was scanned across a small area source, the measured profile or "measured source function", MSF, was expected to be a linear convolution of the "true source function", TSF, with the PSF. Thus the MSF may be expressed as:

$$MSF = PSF ** TSF$$

where the double asterisk stands for execution of the convolution integral. Then, in order to recover the TSF from this instrumental convolution there must be an inversion of the convolution, a procedure which may be symbolized as:

$$TSF = MSF // PSF.$$

In those cases where the diameter of the TSF is less than the diffraction limited width of the PSF, as is true for most of our objects here, it is necessary to invert the convolution integral by an iterative process of successive approximations. The result of a deconvolution, the TSF, is tested by comparing the actual MSF with the calculated convolution of that TSF with the PSF. The two deconvolution procedures used here are one-dimensional versions of the Richardson-Lucy algorithm, R-L, discussed by Heasley (1984) and the "maximum entropy method", MEM, of Frieden (1972) as described by Gull and Daniell (1978). As discussed in Appendix A, the R-L algorithm is simple and fast to execute on a small computer (IBM AT) and was modified from a program in Basic written by George Aumann at IPAC. The MEM algorithm was written in Fortran by Mike Cobb at Steward observatory and is run on a Data General MV 10000. Quite comparable results were obtained with both techniques. For these simple cases other methods may work as well.

An important check on the entire procedure is presented in Figure 1 where the four observations of two point sources, alpha Boo and beta Gru, which had been averaged together to make up the PSF, were individually deconvolved by running 1000 iterations of the R-L algorithm. The excellent agreement between these four independent observations is an indication that the technique gives highly reproducible results on bright sources and that results for the FWHM down to 9 arcsec are to be regarded with some degree of significance. This is about 0.3 of the " diffraction limit". In this sense IRAS has demonstrated the power of "super resolution" as a practical way of increasing the angular resolution of infrared telescopes. The reason that the observations of Hygia are not combined with the two stars is that it was observed with a different detector and is used here as the point source for the observations of NGC 1068.

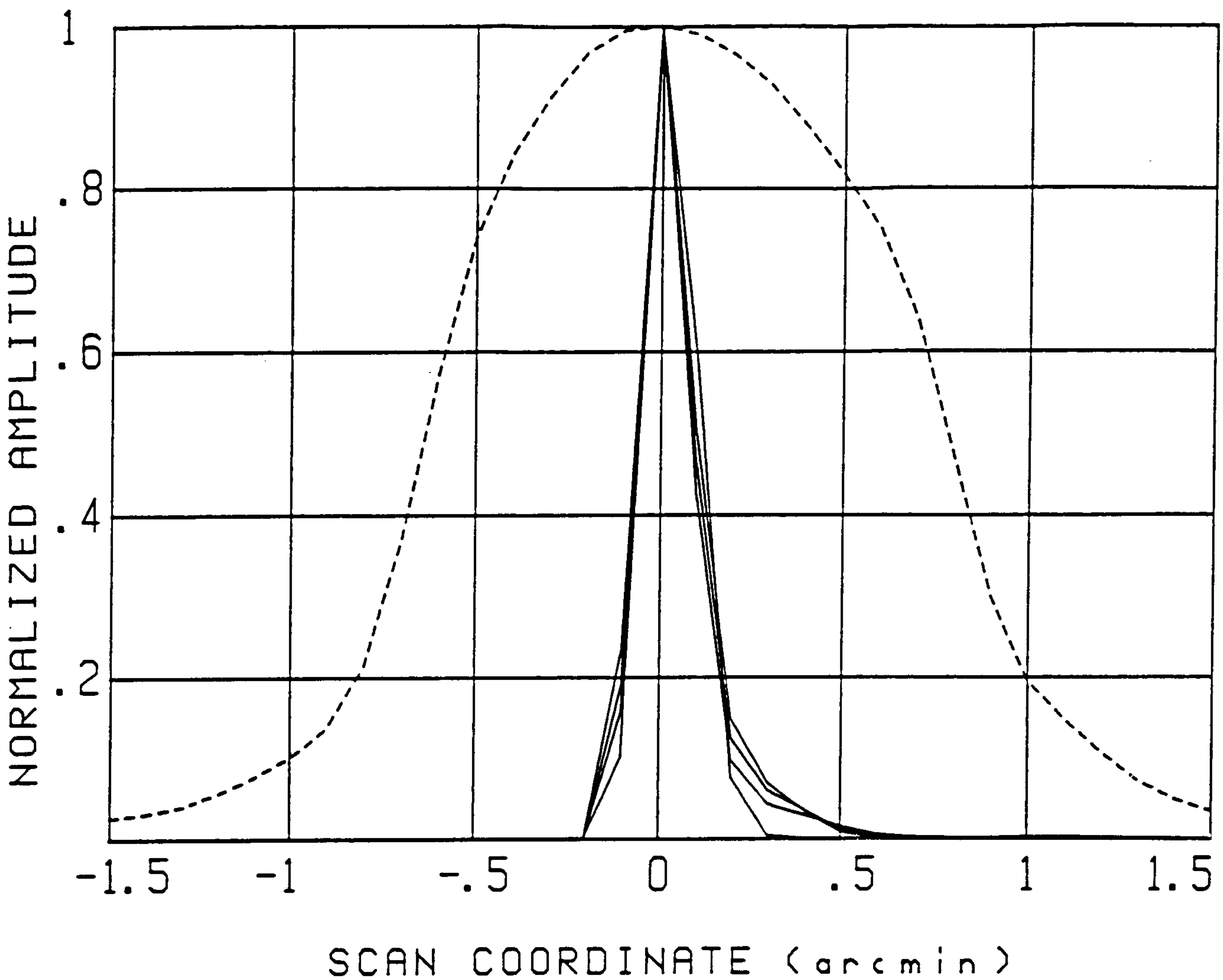

Figure 1. The dashed line represents the 60 micron PSF. The four solid lines represent the four independent observations of the two stars, alpha Boo and beta Gru, deconvolved individually with the PSF. North is to the left.

RESULTS FOR THE "SLOW SCAN" GALAXIES

Figure 2 shows the slow scan PSF, which is the unweighted average of the two point sources, and the MSF curve for M 82 obtained from the two independent observations. When reduced independently there is quite excellent agreement between the two M82 observations. Close examination of Figure 2 reveals the characteristic differences that exist between the point source and the extended source, with the MSF narrower at the top and wider at the base than the PSF. The FWHM for the PSF is 85 arcsec., slightly less than the geometrical width of the detector, as designed and built, of 90 arcsec. The two M 82 observations were taken on successive days and the scan direction was essentially perpendicular to the major axis of the galaxy. As discussed above the obvious asymmetries in these data are not fully understood and it is not yet clear why the extension on the north side of the galaxy appears greater than on the opposite side. Indeed,

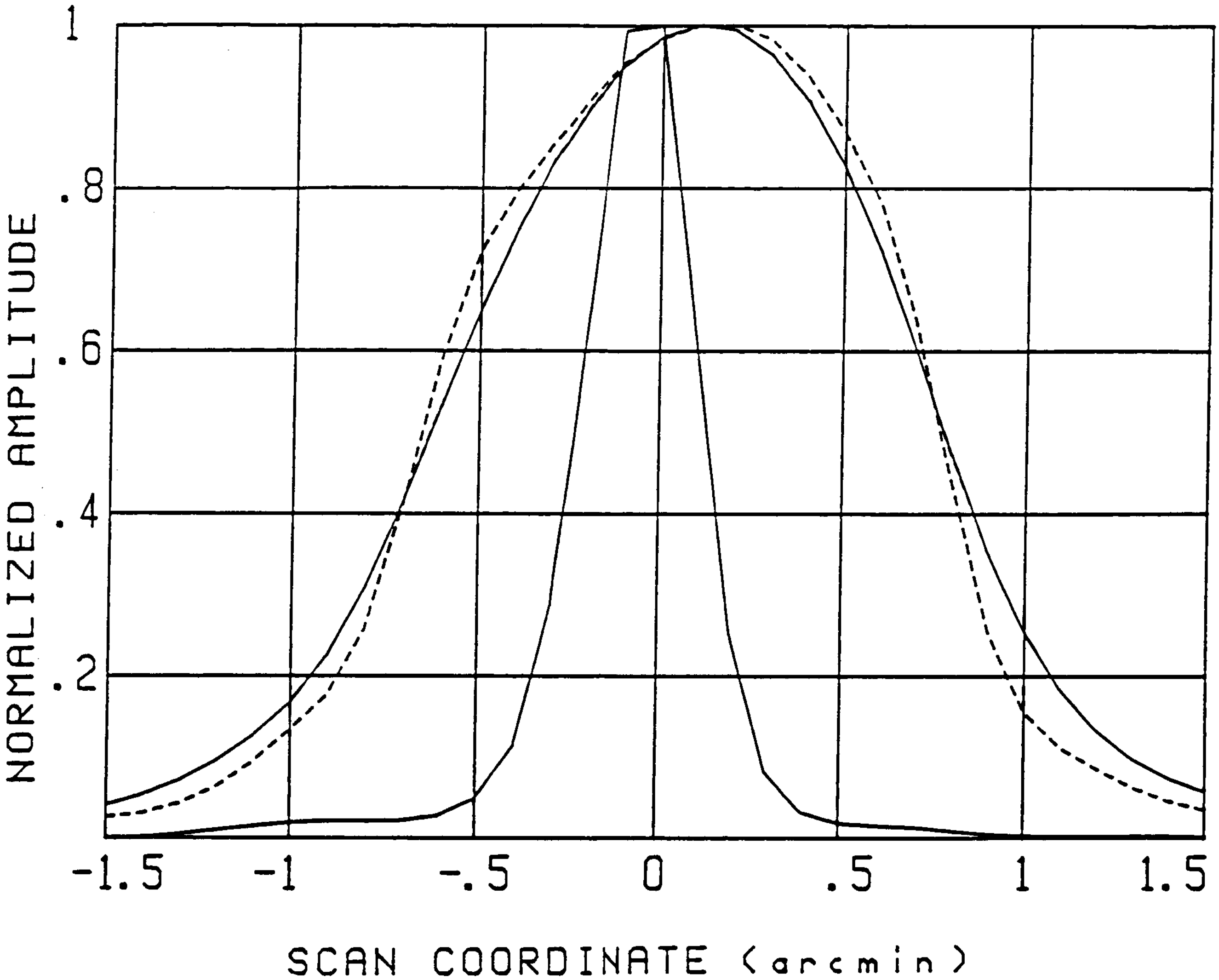

Figure 2. The dashed line represents the 60 micron PSF. The two solid lines represent the MSF and TSF for M 82. North is to the right.

further analysis is needed to determine whether the extended emission, more than one arcmin. from the nucleus, is a real property of the galaxy or a result of instrumental effects. Perhaps these effects are produced by the detector's non-linear behavior, although no satisfactory model has been found to explain this in detail. The measured FWHM is listed in Table 3. Although it is difficult to assess with certainty, the accuracy here would appear to be +/- 1 or 2 arcsec. These IRAS results, in so far as they can be directly compared, are consistent with published airborne measurements of Telesco and Harper (1980).

Figure 3 again shows the PSF for reference and includes the TSF results for NGC 2623, NGC 1068 and NGC 3079, in order of size. NGC 2623 is not clearly resolved but appears to be slightly larger than the PSF. NGC 1068, which was observed with a different detector, was deconvolved using Hygia as the point source; it too shows an asymmetry which is not yet understood from an observational point of view. NGC 1068 is the second brightest source observed

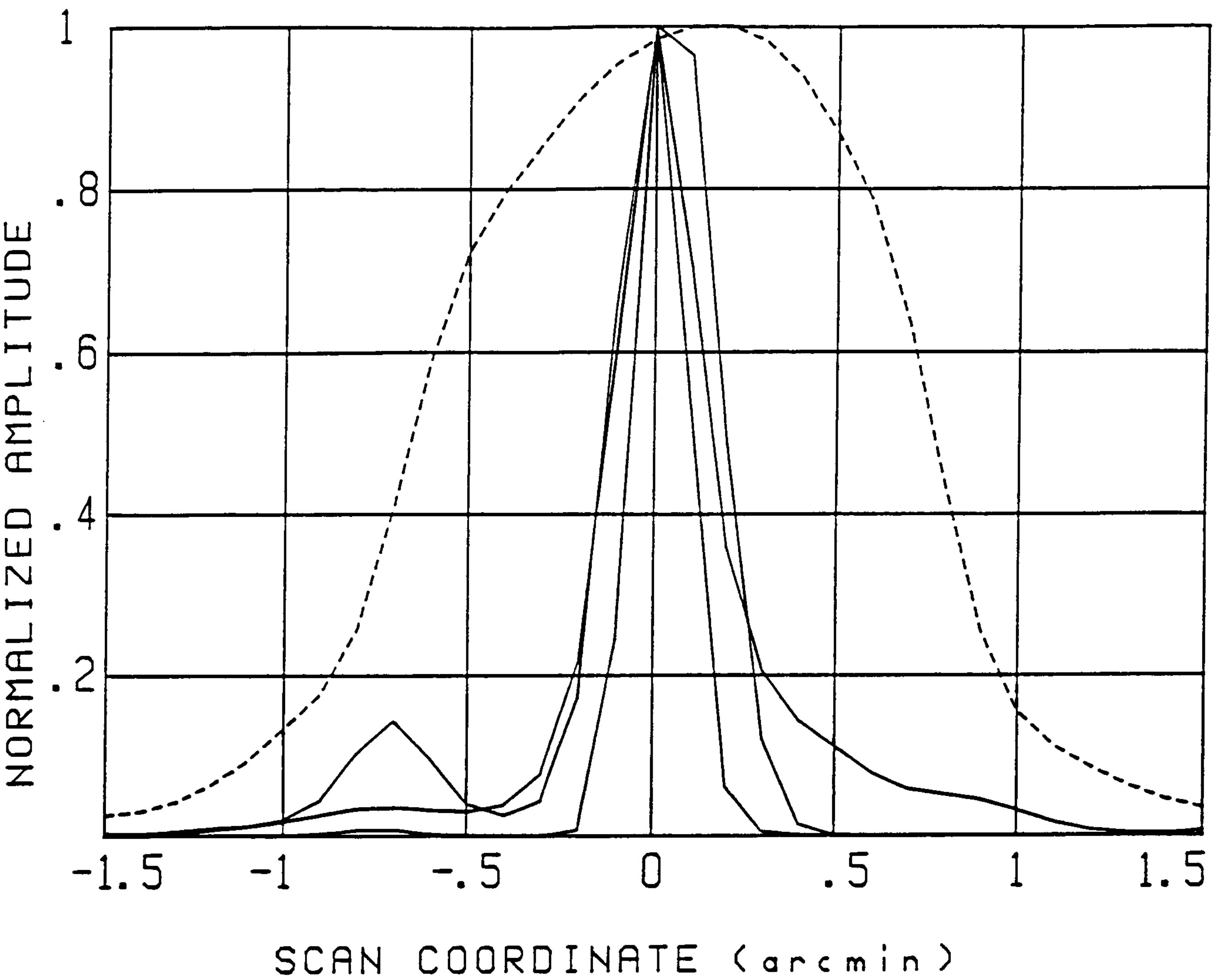

Figure 3. The dashed line represents the 60 micron PSF. The three solid lines represent the TSF for, starting with the smallest source, NGC 2623, NGC 1068 and NGC 3079, respectively. Note that NGC 1068 was deconvolved using Hygia as the PSF and only 500 iterations of R-L were used. North is to the right.

but Hygia is only slightly fainter and does not show any significant differences from the weaker point sources. At this stage of the analysis it is possible that these two galaxies, M 82 and NGC 1068, both have 60 um emission extending outward from their nuclei in an asymmetric fashion and in directions perpendicular to their major axes. Further analysis of these data and study of other IRAS observations are needed to confirm or deny this result. Fortunately, M 82 is so bright that it should be possible to use the Kuiper Airborne Observatory to test this unexplained result.

Finally, the well resolved TSF for NGC 3079 is a classic example of the "core-halo" structure with strong evidence for a second core only 40 arcsec from the brighter core. In this system the enhanced IR activity is spread over very large distances even though most of the infrared emission is, like that of other luminous infrared galaxies, concentrated near the bright nucleus. It appears that we have an opportunity here to study both members of a strongly interacting pair of galaxies.

ADDSCAN OBSERVATIONS

As mentioned above, it is possible to combine the 8 or more redundant survey scans of a given source to construct a well sampled MSF despite the fact that each scan is badly under sampled. It can be seen in Table 2 that the interval between samples is 29 arcsec., almost 3 times the minimum requirement of 10.5 arcsec. to satisfy the Nyquist condition. The computer program used for this work was developed at IPAC and carries the name ADDSCAN. When the position reconstruction is carried out on a series of scans, the signal for each sample is placed in bins only 6 arcsec. apart. Because each scan samples at different locations on the sky, a median average of the 8 or more survey scans effectively fills the gaps by randomly distributing the information in the 6 arcsec. bins.

Using the same stars, alpha Boo and beta Gru, a PSF was constructed from ADDSCAN data and compared to the PSF from the slow scan observations. A slight degradation in the width and shape of the function is apparent but it still contains most of the spatial frequencies present in the slow scan PSF.

Using this new PSF and the MEM algorithm, three galaxies of interest were deconvolved and the results are shown in Figure 4 and in Table 3. The two most luminous objects, Mk 231 and Arp 220 are not resolved and the upper limits are listed in Table 3. The interacting pair, Arp 82, is well resolved, as shown in Figure 4, where it can also be seen that the brighter of these two galaxies is extended. Fortuitously, the scan direction is favorably placed, nearly along the direction of separation, and the measured separation in the IR is within 2 arcsec. of the optical separation. Again it is possible to resolve the two components of a strongly interacting system. The flux density of the brighter component is only 3 Jy. This means that a rather large number of galaxies, of order 2000, can be studied by this technique; of course only a fraction of the total sample will be resolved but this should add extensively to our knowledge of the size and surface brightness of IRAS galaxies.

Table 3. SUMMARY OF RESULTS

GALAXY	DISTANCE (Mpc)	DIAMETER (arcs.)	(Kpc)	EXTENT (arcs.)	(Kpc)	FLUX DENSITY (Jy)	SCAN ANGLE (deg.)
M 82	3	24	0.35	150	2.2	1170	-37
N 1068	12	20	1.16	60	3.5	185	18
N 2623	53	<11	<3	--	--	31	-16
N 3079	18	18	1.6	>120	>10	35	-35
Arp 82	44	40	8.5	180	35	3	--
Arp 220	60	<15	<4.5	--	--	104	--
Mk 231	120	<26	<15	--	--	33	--

Note: DIAMETER = FWHM; EXTENT = the maximum extent of the TSF.
Ho = 1 E 2 km/s/Mpc. Scan angle = position angle measured north of south in the clockwise direction.

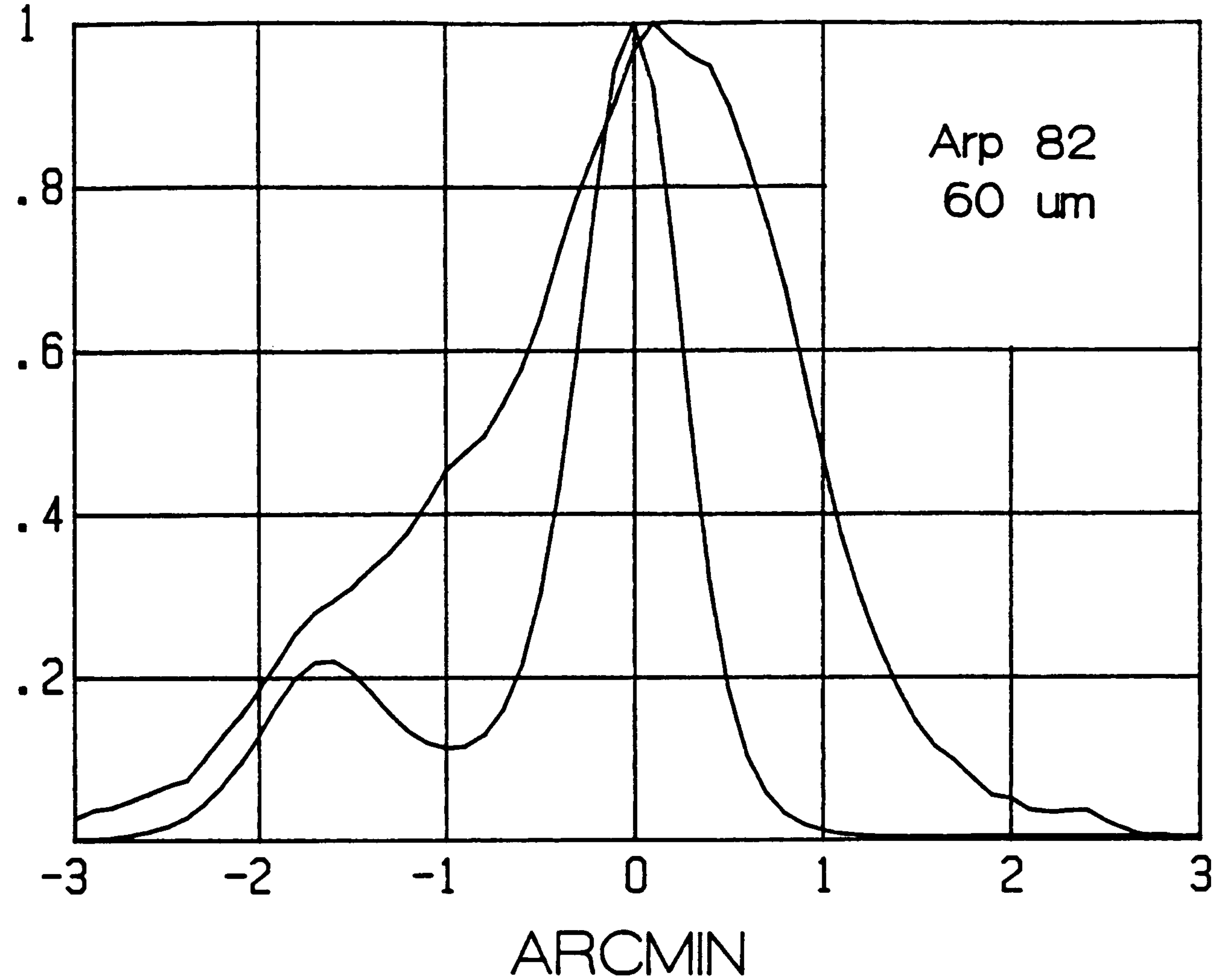

Figure 4. The result of combining all 60 micron survey scans of Arp 82 using "ADDSCAN" and the resulting deconvolution with a 60 micron PSF based on ADDSCAN observations of point sources.

APPENDIX A: The R-L Algorithm

The task of deconvolution is best accomplished by use of a so-called "nonlinear" method of successive approximations. As a practical matter the R-L algorithm offers a number of advantages including simplicity, speed of execution and predictability. Its use here is very much like that of Heasley (1984) except that it is limited to one dimension and the number of iterations used is very much larger. The following brief explanation may serve to remove any ambiguities about the method used, with the largest unsettled question the establishment of an objective criterion for determining the "proper" number of iterations.

Let:

PSF = P(x)
MSF = M(x)
TSF = T(x).

Then:

$$T(x)k = T(x)k\text{-}1[(M(x)/(T(x)k\text{-}1 ** P(x)) ** P(x)]$$

Where:

$$T(X)1 = M(x)[(M(x)/(M(x) ** P(x)) ** P(x)].$$

The data arrays, P(x) and M(x), must be carefully aligned or "phased" and the first iteration simply begins with M(x) as the initial "guess" at T(x); neither array can have zero or negative values. In executing each iteration the convolution integral, which consists of only eight lines of code in Basic, is used twice, first to form the quotient, T ** P, and then to smooth the ratio, M/(T ** P). Progress is rapid for the first few iterations and can be monitored by summing the absolute values of the differences between successive approximations. When tested on perfect data sets, such as the inversion of convolutions of simple functions, there is no tendency to oscillate or to overshoot and 1000 iterations are both productive and practical in terms of run time. The effects of various types of noise and/or distortion and of different degrees of oversampling are relevant to the results given here but are beyond the scope of this brief report.

ACKNOWLEDGMENTS

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DISCUSSION

GEZARI:
What is the uncertainty in the deconvolved source diameters you presented?

LOW:
I believe the error is about ±2 arcsec on the diameter for the bright 'slow scan' observation at 60μm.

JOY:
On the 60μm graph of M82, you show that the point source profile is broader than the M82 profile over the central arcmin or so. How can it be concluded that M82 is resolved on any scale?

LOW:

The simplest way to assure yourself that the effect you mention is real is to consider the case of two step functions, each of width w, convolved together. The result in a triangle of base 2w and half width of w. Clearly, the upper half of the triangle is of width < w.

TELESCO:

M82 and NGC 1068 have already been resolved in the far-infrared on the Kuiper Airborne Observatory and these results are already in the literature. Are your requests consistent with those observations?

LOW:

At present, I believe the IRAS results and the KAO results are in agreement with respect to the sizes of the cores in M82 and NGC 1068. Because the KAO systems use chopping to subtract the background, I do not expect they will agree on the 'wings' of sources.