Mon. Not. R. Astron. Soc. 000, 000–000 (1997) Printed 19 September 1997 (MN LaTeX style file v1.4)

Internal extinction of disc galaxies: I. High resolution extinction map of NGC 6946

M. Trewhella
IPAC, Caltech, M.S. 100-22, Pasadena, CA 91125, USA

Submitted to MNRAS: September 1997

ABSTRACT
Traditionally, it has been believed that extinction effects due to dust within the interstellar medium of external galaxies are rather small and can largely be ignored. Over the last 10 years however, considerable doubt has been cast over the evidence to support this comfortable idea and it became clear that a more detailed analysis was required. Here, a new technique for mapping the extinction in disc galaxies with high resolution is presented.

This technique has been applied to the Sc galaxy NGC 6946. The results show that dust extinction significantly affects both the overall brightness and appearance of the galaxy. The total extinction is found to be $A_B = 0.45$ - somewhat larger than the value of $A_B = 0.2$ usually quoted for an Sc galaxy. When corrected for dust the morphology more closely resembles that of an b rather than an Sc galaxy.

The most surprising result of this work is finding inter-arm regions that suffer high extinction. It appears that these regions appear faint because of the high extinction and not as a result of low stellar density. There are also inter-arm regions that suffer little extinction, these are therefore truly regions of low stellar density.

Key words: galaxies: spiral, individual (NGC 6946) – ISM: dust, extinction.

1 INTRODUCTION

The only means astronomers have to study the physics of extragalactic objects is by measuring the electromagnetic radiation they produce. Embedded in this process is the implicit assumption that the energy we measure represents the true output. This may not be the case for studies of disk galaxies at UV and optical wavelengths. Dust contained within their interstellar media will extinguish some of the light, reducing its measured intensity. As the distribution of the dust (and therefore the extinction) within the interstellar medium is likely to be non-uniform, we could also be misled about the observed morphology of disc systems.

In this introduction, previous investigations and methods used to study opacity are discussed. I will argue the case that none were conclusive, providing clear motivation for a more detailed study.

1.1 Surface-brightness/inclination tests

The first attempt to quantify the dust effects in disc galaxies was by Holmberg (1958), who studied the variation of galaxy surface-brightness with projected inclination. As a galaxy is tilted to higher inclinations, our line of sight intercepts a longer path length of stars, the galaxy should therefore appear brighter. If however, the galaxy contains a large amount of dust then we would only recieve light from one mean free path into it, its surface-brightness would therefore be the same at all viewing angles. By analysing the surface-brightness (or some related property) of a galaxy when viewed at different angles it should be possible to study the dust extinction. Of course, it is not possible to carry it out on an individual galaxy but by using the thousands of known galaxies, projected at random inclinations, it should be possible to carry out this test on a statistical basis. Holmberg did this and concluded that galaxies behaved as though they were optically thin, dust effects were small.

A similar analysis carried out by Heidmann, Heidmann and de Vaucouleurs (1972) reached similar conclusions. This result was included in the RC2 (de Vaucouleurs et al. 1976) catalogue and it became "common knowledge" that galaxies were optically thin.

This remained the case until Disney, Davies and Phillipps (1989) showed the interpretation of how galaxies behave in these tests to be ambiguous. They concluded that, for realistic geometries, galaxies should always behave as though they are optically thin, regardless of their true opacity.

Contrary to this prediction, a year later Valentijn (1990) found that galaxies behaved as though they were totally optically thick. Since his test was carried out at the $B\mu = 26$ isophote he concluded that galaxies were optically thick out

to this radius. For this to happen, there would need to be an another component of dust with a scaleheight perpendicular to the plane larger than that of the stars *in addition* to the dust component which produces the distinctive dust lanes seen in edge-on galaxies. The implication of this result is that optical observations of galaxies barely scratch the surface, and our understanding of galaxies may need to be revised. Burstein, Haynes and Faber (1991) and Choloniewski (1991), postulated the existence of surface-brightness selection effects in Valentijn's sample. These were later shown to exist by Davies *et al.* (1993). Burstein *et al.* (1991) and Choloniewski (1991) removed the selection biases present in Valentijn's test by requiring that distances be known to all galaxies in the sample. Despite this, they also found that galaxies behaved as though they were optically thick, adding further weight to the suggestion that our understanding of extinction in disc galaxies needed reviewing.

The results of Burstein *et al.* (1991) and Choloniewski (1991) were shown to suffer from a new selection effect by Davies *et al.* (1995). The telescopes used to obtain the redshifts had a maximum range of 12000km/s, which is not large enough to contain a representative sample for this test. Davies *et al.* (1995) showed that the Burstein *et al.* (1991) test always predicts high opacity for a redshift cut-off of 12000km/s, regardless of the true opacity. The cut-off would need to be extended to 24000km/s for the test to work. At this point in time, it seemed that not only could we not relate how galaxies behave in a surface-brightness/inclination test to their opacity but we could not even measure how they behave.

Recently, Jones *et al.* (1996) showed that the selection effects can be modelled and actually used to investigate the opacity. The UGC, ESO and RC2 catalogues all seem to behave as though they are optically thin, as predicted if the standard geometry applies (Disney *et al.* 1989). Of course this still doesn't mean that they are actually optical thin but knowing how they behave gives hope that we may be able to correct measured galaxy diameters and magnitudes to some universal scale for comparison (e.g. face-on), even if that scale isn't dust free.

1.2 Energy balance

When optical energy is absorbed by dust it is not destroyed, it will heat the dust which will then re-radiate the energy at far infrared wavelengths. If we compare the optical to the far infrared energy output of a galaxy we should be able to study its opacity.

Jura (1980) argued that the constancy of galaxy surface-brightness (Freeman 1970) could be caused by dust in their interstellar media. Jura (1982) predicted that if galaxies were optically thick then the forthcoming IRAS mission should be able to detect them with ease.

However, when the IRAS mission flew and unexpectedly detected thousands of galaxies with high far infrared outputs, the cause was not attributed to opacity but to star formation. After all, galaxies were known to be optically thin. Whether the far infrared emission is due to star formation or general disc opacity is at some level semantics. Everyone agrees that the observed far infrared energy is due to starlight that has been absorbed and re-radiated by dust. The problem is that stars are formed in compact regions of high opacity that may dominate the infrared emission but contribute little to the overall disc opacity. The debate between star formation and disc opacity as the source of the far infrared radiation is thus equivalent to determining the level of clumpiness present in the emmission. The poor resolution of the IRAS satellite ($\sim 1'$) cannot distinguish between the two scenarios.

The most common way used to separate the dust heating due to the general disc extinction from that in starforming regions is to examine the spectrum (typically 4 IRAS points at 12, 25, 60 and 100μm). The most simple deconvolutions have two components. Each component has two free parameters, temperature and normalisation (mass). The uncertain long wavelength emissivity index (β) adds another degree of freedom and already the problem becomes overparameterised. Not surprisingly, the large number of authors that have attempted this deconvolution using different initial assumptions and models have reached a wide range of conclusions about the dominant source of the far infrared emission (Xu and Helou 1990, Rowan-Robinson 1992, Devereux and Young 1993, and Evans 1995) leading to large uncertainties in the opacity debate. Another cause of uncertainty is the lack of observations beyond 100μm, the peak dust emmission is expected to occur at wavelengths of 100 - 300μm, the IRAS satellite may therefore have missed a large fraction of the energy output. Far infrared imaging cannot resolve these uncertainties until data with better angular and/or spectral resolution is available.

1.3 Optical-NIR imaging

A common technique for measuring the extinction to stars in our Galaxy is to use the colour excess. For example, the $(B - V)$ colour excess is given by,

$$\underbrace{E(B-V)}_{\text{excess}} = \underbrace{(B-V)}_{\substack{\text{observed}\\ \text{colour}}} - \underbrace{(B-V)_0}_{\substack{\text{intrinsic}\\ \text{colour}}} \qquad (1)$$

$$A_B - A_V$$

where A_B is the B band extinction in magnitudes and A_V is the V band extinction in magnitudes. For a screen model (applicable to stars in our Galaxy) the ratio of extinction at different wavelengths is fixed for given dust properties (the extinction law). If a star's spectral type is known (and therefore its intrinsic color), the extinction towards it can be simply determined. This technique cannot be simply applied to a whole galaxy because the relative extinction at different wavelengths is sensitive to the unknown relative geometry of stars and dust and is not constant for different optical depths.

Block *et al.* (1994) argued that by using near infrared observations it is possible to extend this technique to galaxies. They argued that because the optical depth in the K band is 10× smaller than in the B band, the extinction in the K band (A_K) can be neglected. Equation 1 then becomes,

$$E(B-K) = (B-h')-(/1-A')" \qquad (?)$$

$$A_B - A_V$$

A_B

Block *et al.* (1994) argued that this technique was powerful because it didn't depend on uncertain geometry or clumpiness; it didn't require observations at wavelengths longer than $100\mu m$; the observations were simple to carry out and could be done on the ground; and the resulting map of extinction has a resolution of $\sim 1''$, compared to $> 1'$ from other techniques.

There are two main problems with this technique,

(i) $A_K \neq 0$. For a screen model with a Galactic extinction law $A_B/A_K = 10$ but for other geometries it depends on the optical depth. Some simple trials with more realistic geometries give $1 < A_B/A_K < 10$.

(ii) $(B - K)_0$ is unknown, there is no "spectral type" with well defined colours for galaxies. Not only is the intrisic colour unknown, it cannot be measured directly because of the extinction. It is also likely that the intrinsic colour of the underlying stellar distribution will vary with position in the galaxy, e.g. the bulge is unlikely to have the same colour as the disc

2 NEW METHOD

The method proposed here is actually a combination of the colour map and an improved energy balance method. It is possible to combine them in a way that keeps the good points of both - the good overall normalisation of the energy balance and the spatial resolution of the colour maps.

Our updated energy balance (see below) gives the total extinction in a cell comparable in size to the FIR beam. This low resolution measurement of extinction is then used to define a calibration constant (equation 3) that is applied to every colour map pixel that falls within the cell to give the extinction of that pixel (equation 4).

Re-arranging to combine the two unknowns in equation 2 gives,

$$A_B(cell) - (B - K)(cell) = \underbrace{A_K(cell) - (B - K)_0(cell)}_{C_{cell}} \quad (3)$$

The extinction per pixel is then given by,

$$A_B = (B - K) + C_{cell} \quad (4)$$

where C_{cell} is the calibration constant of the cell that the pixel falls in. The net result is an extinction map that has both high resolution and absolute normalisation.

2.1 Improved energy balance

An energy balance is performed on each cell independantly The energy balance used here makes the following improvements on those performed previously (see section 1.2).

(i) The *total* extinction from all sources is required to calibrate the colour map. It is not therefore necessary (and in fact would be wrong) to seperate star formation from general interstellar extinction as sources of dust heating.

(ii) Infrared Space Observatory* (Kessler *et al.* 1996) observations at $200\mu m$ are used to constrain the spectral energy distribution beyond $100\mu m$. The total far infrared energy is obtained by fitting two "modified black body" components to five 5 infrared spectral points (12, 25, 60, 100 and $200\mu m$).

(iii) Far infrared contributions are considered from the full range of wavelengths that stars emit over. Often in the past, only the B band has been considered (Saunders *et al.* 1990). The optical spectral energy distribution is determined by fitting 2 black body components to several (≥ 5) broad band band flux measurements. This "spectrum" is then split up into 10 "bands" covering the range from $0.1 - 2.5\mu m$. An initial guess is made at the B band optical depth and the optical depths in all the other bands are predicted using the Galactic extinction law (Bianchi *et al.* 1996). The amount of light lost (and hence redistributed into the far infrared) from each band is calculated using a radiative transfer model that assumes that the dust and stars are distributed exponentially above the disc but does not include the effects of scattering. The far infrared energy predicted for each band is summed and the total compared to the observed total and the trial B band optial depth is modified. This is repeated until the prediction matches the observations.

The most likely estimates of the extinction and optical depth are produced using the best fitting spectra (optical and far infrared) and the standard dust/star geometry ($\zeta = \beta_d/\beta_s = 0.5$). Rather than attempting to derive some error limit on these numbers it was decided to determine the maximum and minimum values that could concievably be consistent with the data. The maximum extinction is obtained by combining the lowest total flux optical fit with the highest total flux far infrared fit and using a high value of the layering parameter ($\zeta = 0.7$). The minimum extinction is obtained by combining the highest total flux optical fit with the lowest total flux far infrared fit and using a low value of the layering parameter ($\zeta = 0.3$). The maximum optical depth is obtained by using the lowest total flux optical fit with the highest total flux far infrared fit and a low value of the layering parameter ($\zeta = 0.3$). The lowest value of the optical depth is obtained using the highest optical flux fit with the lowest far infrared flux fit and a high value of the layering parameter ($\zeta = 0.7$).

3 DATA

3.1 Observations

Optical maps in the B, V, R and I bands were obtained in April 1996 at the 0.9m telescope at Kitt Peak using the t2ka CCD camera, which has 2048×2048 pixels of $0.68''$ each, giving a field of view of $23.2'$. The total exposure times were 20 minutes in the B, V and R bands and 10 minutes in the I band. The images were reduced using STARLINK software and calibrated using the aperture photometry of Engargiola (1991).

* Based on observations with ISO, an ESA project with instruments funded by ESA Member States" (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) with the participation of ISAS and NASA.

A near infrared map in the K band was obtained in November 1995 at the 2.5m Wyoming Infrared Observatory using MIRC, which has 128×128 pixels of $2.23''$ each giving a field of view of $4.7'$. The final picture is made up of a 2×2 mosaic with an integration time per position of 24 minutes. The images were reduced using STARLINK software and calibrated using the aperture photometry of Aaronson (1977).

Calibrated IRAS HiRes far infrared maps at 12, 25, 60 and $100\mu m$ were obtained from IPAC. These have a resolution of $60 - 100''$ (FWHM), are sampled onto a $15''$ grid and cover a $1^\circ \times 1^\circ$ area.

A far infrared map at $200\mu m$ was obtained in December 1996 using the C200 detector of the ISOPHOT instrument (Lemke *et al.* 1996) aboard the Infrared Space Observatory. The maps were made using oversampling mapping mode (AOT P32), the sampling along the in-scan and cross-scan directions was $31''$ and $93''$ respectively. Reduction of the data was carried out using the ISOPHOT interactive analysis software package (PIA v6.0†), allowing correction for non-linearity in the detectors and deglitching. The signal was converted to MJ/sr using the internal fine calibration source, which was observed before and after the galaxy to monitor detector responsivity drifts. The final map has $31''$ pixels and a resolution of $117''$ (FWHM). The map covers an area of $\sim 22' \times 18'$.

3.2 Additional processing

The local background (sky in the optical and near infrared and cirrus in the far infrared) was subtracted from each image. The contribution to the overall flux from local stars was eliminated by masking the stars by eye. The galaxy flux in the masked regions was estimated using a 2D linear interpolation of the flux in the surrounding area. This treatment was required for many stars in the optical and near infrared but only one star was visible in the far infrared.

All the data was smoothed to the worst resolution of $117''$, ISO at $200\mu m$ (Tuffs *et al.* 1996). In the optical and near infrared, this was achieved by smoothing with a gaussian of $117''$. For the IRAS images, an initial guess was made at the required smoothing gaussian by assuming that the FWHMs of the gaussians add together in quadrature. This initial guess was used to smooth the IRAS beam maps in the vicinity of NGC 6946 (a standard product with HiRes data) and the resulting beam size and shape was measured. The initial guess was adjusted until the beam became circular with a FWHM of $117''$.

Finally, the ISO $200\mu m$ data was binned up by a factor of 4 in each direction giving a map with $124''$ pixels (cells). These were chosen to be just larger than the beam size to ensure that each cell was an independant sample. The smoothed maps at all the other wavelengths were transformed and re-sampled onto the same grid using the central peak in flux as a reference point and converted into units of Janskys (per cell). The $200\mu m$ and the B band cell maps are shown in figure 1 as an example.

A fortran program was then written to read in the flux values from each of these 10 maps, fit the spectrum and calculate the extinction and optical for each cell. The outputs were written into 6 images of the best, highest and lowest optical depth and extinction.

To make the $(B - K)$ colour maps, the B band image was transformed and re-sampled to have the same size, orientation and pixel scale as the lower resolution K band image. The K band image was divided by the B band image and the resulting map converted to a magnitude scale.

4 NGC 6946

NGC 6946 is an Sc galaxy viewed at an inclination of $i = 31^\circ$ that lies at a distance of 5.5Mpc (Tully 1988). At this distance an angle of $1''$ corresponds to a physical size of $\sim$25pc. NGC 6946 is thought to have active star formation throughout its disc and a mild starburst in its centre (Tacconi and Young 1990). Its spiral arms structure has been classified as 9 by Elmegreen and Elmegreen (1984), in this classification scheme, type 6 corresponds to flocculent arms and type 12 to classic grand design spiral structure. Tacconi and Young (1990) identify six spiral arms emanating from the centre. The most striking of these is the strongly developed, luminous arm in the NE, in contrast with poorly defined spiral structure in the SW. The B band image (transformed to the same size, orientation and pixel scale of the K band image) is shown in figure 2.

4.1 Energy balance results

The optical depth and extinction maps are shown in figure 3. The optical depth is shown on the left and the extinction on the right. The top maps show the most likely values, the middle maps show the lowest possible values and the lower maps show the highest possible values. The extinction and optical depth represented by each colour is shown by the key at the top of each column. Each cell corresponds to a physical size of $\sim$3kpc. It can be seen that the extinction in the centre is high ($A_B = 0.8$ means that only 45% of the B band light escapes) and that it drops off towards the outer regions of the galaxy (>75% escapes there). The total extinction of the whole galaxy is $A_B = 0.45$, considerably higher than the $A_B = 0.2$ prescribed for an Sc galaxy in the RC2.

The extinction maps are constrained reasonably well considering the large variation of estimates between previous studies (see introduction), there is only a 0.3 magnitude difference between the maximum and minimum and the best fitting values‡.

The maps of the absorption optical depth are less well constrained but show that at least the central regions of

† PIA is a joint development by the ESA Astrophysics Division and the ISOPHOT Consortium led by the Max Planck Institute for Astronomy (MPIA), Heidelberg. Contributing ISOPHOT Consortium institutes are DIAS, RAL, AIP, MPIK, and MPIA.

‡ The maximum and minumum values are derived by combining the most extreme fits in the most extreme ways. It is very unlikely that the errors could conspire to combine in this manner, the full range of possible values thus represents a much larger range than the true uncertainty.

NGC 6946 are likely to be optically thick, even in the minimum map. The current observations and understanding of geometry cannot completely rule out the possibility that NGC 6946 is optically thick over the entire face of its disc, as suggested by Valentijn (1990, 1994).

The maps in figure 3 show the absorption optical depth, the total optical depth (including scattering) is likely to be double this (see section 5.1). These results therefore seem to suggest extremely high optical depths. If the dust is patchy, however, these values represent the *average* optical depth. This average could well be made up of small regions of high optical depth with largely transparent regions in between. The high optical depths need not necessarily imply such a large effective opaque cross section to background objects.

4.2 Extinction map

The high resolution extinction map is shown in figure 4. The extinction is shown in magnitudes (A_B) with the scale indicated. The first thing to note about the extinction map is the absolute scaling between cells. In the central regions the scaling matches exactly, although in the outer regions where the data becomes noisy the match is not so good. The energy balance was carried out completely independently on each cell, there were no constraints placed on any of the spectrum fitting or the optical depth and extinction calculations. To find that the independent energy balance results from individual cells are consistent would be re-assuring, to find as good a match as shown in figure 4 provides evidence that the techinique is reproducible and fairly accurate.

The extinction map shows that there are two quite distinct causes for an apparent lack of light in a B band image. The B band intensity at a given position can be faint either because it it intrinsically faint or because there is an abnormally high dust extinction present. What appears to be an apparent inter-arm region between the two prominent North-East arms is shown to be the site of strong extinction. Note also how the filamentary dark structures that wind along and across the arms in the B band image are picked out as high extinction regions. In constrast, the inter-arm region in the North-West shows almost no extinction. This is therefore a true inter-arm region with a low stellar density.

One interesting feature to note on the extinction map is the very high extinction in the centre. In the central regions less than $< 4\%$ of the B band light escapes the galaxy. The central peak in extinction does not correspond exactly to the centre of the galaxy, it is actually located approximately 6 pixels ($\sim 300pc$) South West of the optical centre. As heavy dust extinction is associated with active star formation, it is likely that this is the site of the nuclear starburst. Strong evidence that the feature is real and due to dust is provided by high resolution aperture synthesis CO observations of NGC 6946 (Ishizuki *et al.* 1990). They find a small, barely resolved, feature in the observations that is interpreted as a disc of molecular material at the centre of NGC 6946. Examination of their contour map shows that this disc of material is offset from the centre, and corresponds well in size and shape to the extinction feature. The resolution of the extinction map however, is $> 2\times$ better showing the power of this technique to achieve high resolution.

4.3 Dust free map

If the amount of light lost due to dust at every position in a galaxy is known, it is possible to add this extinguished light to the original image to obtain a picture of the galaxy as if it were seen without dust. This "dust free" map of NGC 6946 is shown in figure 5 with the same size, orientation and linear intensity scale as the observed image (figure 2). The most obvious thing to note is the relative brightness of the images, the reconstructed image is considerably brighter than the observed image. This demostrates how effective dust can be at extinguishing starlight. The other clear difference between the images is the morphology. The bulge is much more prominent in the reconstructed image. If NGC 6946 had been viewed without dust, it would likely have been classified as an Sb galaxy **not** an Sc!

5 DISCUSSION

In the introduction some unanswered questions were posed, these will now be discussed and reviewed in light of the results of this investigation.

Extinction It was shown that the extinction of optical light due to dust in the interstellar media of disc galaxies can be mapped with high resolution. The extinction in NGC 6946 was shown to be very patchy and to be somewhat influenced by the spiral structure in the galaxy. It is not clear whether these changes in extinction are caused by changes in the dust mass or dust/star geometry. Stirring the dust up so that it lies in front of the emitting material may be a far more effective way of producing high extinction than increasing the amount of dust present.

It was shown that extinction can have a dramatic effect on the observed morphology of a galaxy. NGC 6946 appears more like an Sb galaxy rather than an Sc when the extinction is corrected for. The implications in terms of galaxy classification are not yet clear. Do Sb galaxies look like Sas when corrected for extinction or are Sc galaxies just dusty Sbs?

Optical depth Although it has been a focus of attention in this field for some time, the optical thickness of disc galaxies is, in some ways, a less important quantity than the extinction. Much of the concentration of effort on determining the optical may well have resulted from the historical notion that extinction and optical depth were essentially equivalent (Trewhella *et al.* 1997), this is only true where the screen geometry applies (Disney *et al.* 1989). This geometry doesn't apply to the internal extinction of discs but it does apply to the obscuration a galaxy will present to a background source. It was shown in Trewhella *et al.* 1995 that, if galaxy optical depths were as high in the outer regions as claimed by Valentijn (1990, 1994), Burstein *et al.* (1991) and Choloniewski (1991), a large fraction of the universe could be hidden beyond a redshift of $z = 3$. If NGC 6946 is taken as a typical galaxy, these results suggest that the universe is transparent out to reshift of $z > 6$. Of course, NGC 6946 may not be a typical galaxy and more galaxies need to be studied to confirm this.

Dust distribution Several papers have suggested the existence of a cold component of dust that is invisible to the IRAS observations and has scale lengths in the radial and

vertical directions larger than those of the stars (Valentijn 1990 & 1994, Burstein *et al.* 1991, Choloniewski 1991 and Beckman *et al.* 1996). The evidence suggesting the existence of this component has been shown to suffer from selection biases (Davies *et al.* 1995) or be explainable by other means (de Jong 1996). There is however, some evidence in the ISO data on NGC 6946 as well as the COBE maps of the Galaxy to suggest that this component does actually exist (Davies *et al.* 1997a & 1997b). This cold dust component probably contains 4–10× the mass of the warmer component although its energy output and hence extinction does not dominate except in the outer regions.

5.1 Sources of error

Scattering does not destroy optical light, it merely changes its direction. For a thin screen geometry, any change in direction removes light from the beam and is equivalent to having destroyed it. For other geometries however, this is not the case. For a spherically symmetric geometry, to first approximation (single scatterer scattering has little net effect - as much light is scattered into any beam as scattered out of it. As the scattering and absorption optical depths are approximately equal in the B band, the total optical depth required to produce a given extinction is approximately double the absorption optical depth.

If multiple scattering occurs, each photon must take a longer path in order to exit the galaxy. This results in increased absorption, lowering the required optical depth for a given extinction. Furthermore, the results of Bianchi *et al.* (1996) show that scattering in disc systems is not isotropic, light is preferentially scattered out of the plane. As a result, using the far infrared energy output may slightly overestimate the extinction of face-on galaxies and underestimate the extinction of edge-on galaxies. The effect is small however, < 0.2 magnitudes for extreme inclinations. This small error in extinction may introduce much larger errors in the optical depth however.

If the dust is clumpy, the effects of scattering are greatly reduced, each clump behave like a large absorbing grain.

In summary, the total optical depth can be estimated from the absorption optical depth by multiplying by 2. In addition to this increase, the unmodelled effects of scattering could introduce large errors in the derived optical depth, up to a factor of 2. The calculated extinction is not so susceptable to errors introduced by neglecting scattering, in NGC 6946 the introduced error is likely to be less than 0.1 magnitudes.

Geometry Running the models with different geometries shows that the measured extinction remains relatively constant (less than 10% change) when the layering parameter (ζ) is varied from 0.1 -- 0.9. As with scattering, the optical depth is much more susceptable to changes in the model, increasing the uncertainties in its determination.

If the dust is clumped, it can have one of two effects. If the clumpiness is random with respect to the stars, it will make the extinction "greyer", i.e. the extinction as a function of wavelength will be more equal. This will have the effect of increasing the contribution of the red and infrared light to the far infrared. If the clumpiness of the dust is correlated with the clumpiness of the young stars, as may be the case (Xu and Helou 1996), it will increase the contribution of the UV and blue light to the far infrared.

It is not clear exactly how either situation would affect the B band extinction and as little is currently known about the way in which dust clumps with stars it is not included in this study, although future knowledge of this could have bearing on these results.

SED fitting As the extinction in a disc system varies slowly with wavelength, the strongest factor in deciding how much a particular band contributes to the far infrared is how much light there is to extinguish. It is therefore important to sample as much of the optical SED as possible to improve the accuracy of the fits. In this work the optical SED is sampled at 5 points from 0.4 to 2.2μm. If the energy output shortward of 0.3μm is significantly larger than the extrapolation of the fits then the UV extinction will be under estimated. If this is the case then the extinction in the other bands will be over estimated to compensate. Observations at shorter wavelengths are required to investigate this possibility.

Although it appears that the peak in dust emission lies somewhere between 100 and 200μm, there may still be some emission at wavelengths longer than 200μm and this should be measured with sub-mm observations.

Resolution The intrinsic colour of the ensemble of stars in a galaxy at any point is likely to vary with position. The resolution of the calibration constant would ideally be better than the likely distance scale over which the intrinsic colour is likely to vary. The most dramatic colour changes are likely to occur in the spiral arms, thus the resolution should be of order the width of an arm. This goal is not quite achieved in NGC 6946, due to the poor resolution of the C200 detector on ISO. It is therefore possible that the high extinction calculated in the North-East inter-arm region could be the result of very blue stars in the spiral arms. Although this is likely to contribute to the amplitude of the calculated extinction differences at some level, it is unlikely to be the dominant cause of the feature for the following reasons. If the calculated extinction feature were due to colour variations alone, both inter-arm regions would show up as having high extinction, this is not the case. The inter-arm region that shows high extinction has a very filamentary structure in the B band image and shows obvious dust lanes crossing the arms. In contrast the low extinction inter-arm regions appears smooth and relatively dust free in the optical image.

5.2 Future work

ISO observing time was awarded to map a total of 10 disc galaxies at 200μm. These galaxies are are of mixed morphological type and have different levels of infrared output and starburst activity which will allow us to examine the importance of these properties on the energy balance and the extinction.

The radiative transfer models will be improved to take into account scattering and clumpiness.

The wavelength coverage of the observations both in NGC 6946 and the other galaxies will be extended to cover the foil range from UV to sub-mm. This will be achieved with the addition of ground based U band CCD imaging; space based ultra-violet imaging from the ASTRO missions; full grating spectra from 42 – 197μm from the LWS instrument on ISO; and sub-mm mapping at 350μm from SHARC at the CSO and at 450 and 850μm from SCUBA at the JCMT.

6 ACKNOWLEDGMENTS

I acknowledge and appreicate the support of a PPARC Ph.D. studentship at the University of Wales Cardiff where this research was carried out. For the observations, I thank the time allocation committees of ISO, WIRO and KPNO; the IPAC staff; and Harley Thronson and Nick Devereux for their efforts. The paper benifitted greatly from discussions with Jon Davies, Paul Alton, Simone Bianchi, Nick Kylafis, Manolis Xilouris, John Beckman and Barry Madore. I acknowledge the support of a JPL postdoctoral fellowship whilst writing this paper.

REFERENCES

Beckman J., Peletier 1{., Knapen J., Corradi R. and Gentet L., 1996, Ap. J, **4G7,** 175

Bianchi S., Ferrara A. and Giovanardi C., 1996, ApJ, 465, **1 2 7**

Block D., Witt A., Grosbol P., Stockton A. and Moneti A., 1994, A&A, **2(XI,** 396

Burstein D., Haynes M. and Faber S., 1991, Nature, 353, 515

Choloniewski J., 1991, MNRAS, 250, 486

Davies J., Phillipps S., Boyce P. and Disney hf., 1993, MNRAS, 260, 491

Davies J., Jones H. and Trewhella hi., 1995, MNRAS, **273,** 699

Davies J., Trewhella M., Jones H., Lisk C., Madden A. and Moss J., **1997,** MNRAS, 288, 679

Davies J., Alton P., Trewhella M. and Bianchi S., **1997,** MNRAS, submitted

de Jong R., 1996, A&A, **31.3,** 377

de Vaucouleurs G. de Vaucouleurs A. and Corwin H. G. Jr., 1976, Second Reference Catalogue of Bright Galaxies (RC2), University of Texas Press

Devereux N. and Young J., 1993, **AJ, 106,** 948

Disney M., Davies J. and Phillipps S., 1989, MNRAS, **239,** 939

Elmegreen D. and Elmegreen B., 1984, ApJS, **54, 127**

ngargiola G., 1991, Ap JS, 76, 875

Evans Rh., 1995, in "The Opacity of Spiral Disks", Cardiff, July 1994 eds. Davies J.I. and Burstein D., Kluwer

Freeman K.C., **1970,** ApJ, 160, 811

Giovanelli R., Haynes hi., Salzer J., Wegner G., da Costa 1,. and Freudling W., 1994, **AJ, 107, 2036**

Holmberg E., 1958, Medd. Lunds. Astr. Obs., Ser. **2,** No. 136

Heidmann J., Heidmann N. and de Vaucouleurs G., 1972, Mem. R. Astr. **Sot.,** 75, 85,

Heidmann J., Heidmann N. and de Vaucouleurs G., 1972, Mem. R. Astr. Soc., 76, 105,

Heidmann J., Heidmann N. and de Vaucouleurs G., 1972, Mem. f{. Astr. Sot., 76, 121

Ishizuki S., Kawabe R., Ishiguro hi., Okumura S., Morita K., Chikada Y., Kasuga T. and Doi M., 1990, Ap J, **355, 436**

Jones H., Davies J. and Trewhella M., 1996, MNR **AS, 283,** 316

Jura **hi.,** 1980, ApJ, 238, 499

Jura M., 1982, ApJ, 254, 70

Kessler M.F. et **al.,** 1996, A&A, **315,** L27

Lemke, D. **et al,** 1996, A&A, **315,** L64

Rowan-Robinson M., 1992, MNRAS, 258, 787

Saunders W. Rowan-Robinson M., Lawrence A., Efstathiou G., Kaiser N., Ellis R. and Frenk C., 1990, MNRAS, 242, 318

Tacconi [,. and Young J., 1990, ApJ, 352, 595

Trewhella M., Davies J., Disney M. and Jones ff., 1997, MNRAS, 288, 397

Tuffs R. J. et al., 1997, A&A, **315,** L149

Tully f{., 1988, Nearby Galaxies Catalog, (Cambridge: Cambridge University Press)

Valentijn E., 1990, Nature, 346, 153

Valtentijn E., 1994, MNRAS, 266, 614

Xu C. and Helou G., 1990, ApJ, 456, 152

Figure 1. The B band image (top) and the 200μm image (bottom) after processing into cell maps

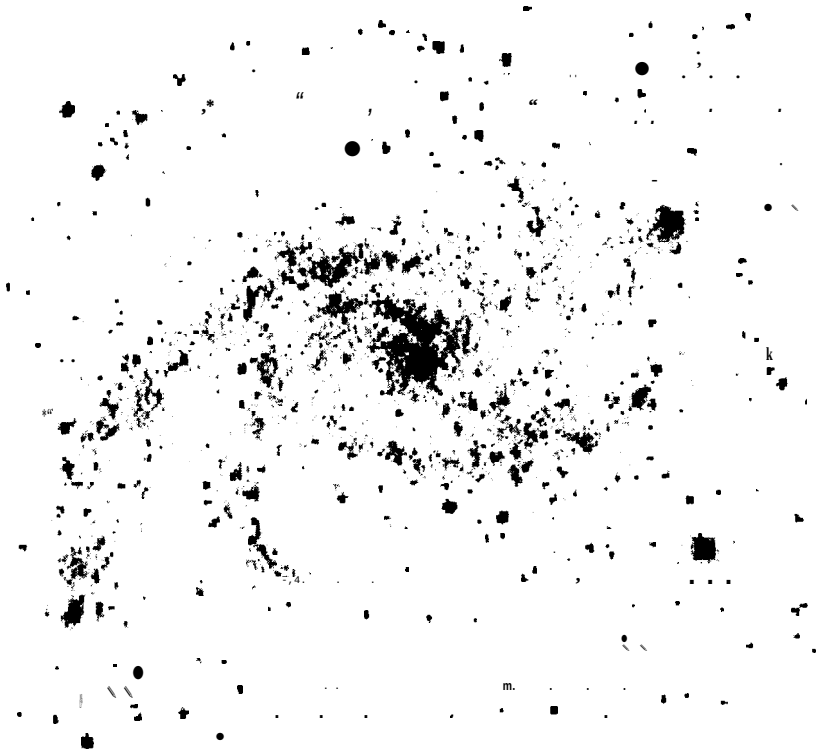

Figure 2. B band image of NGC 6946. North is to the top left and East to the bottom left. The pixel scale is 2.23″ corresponding to 60*pc* in the galaxy.

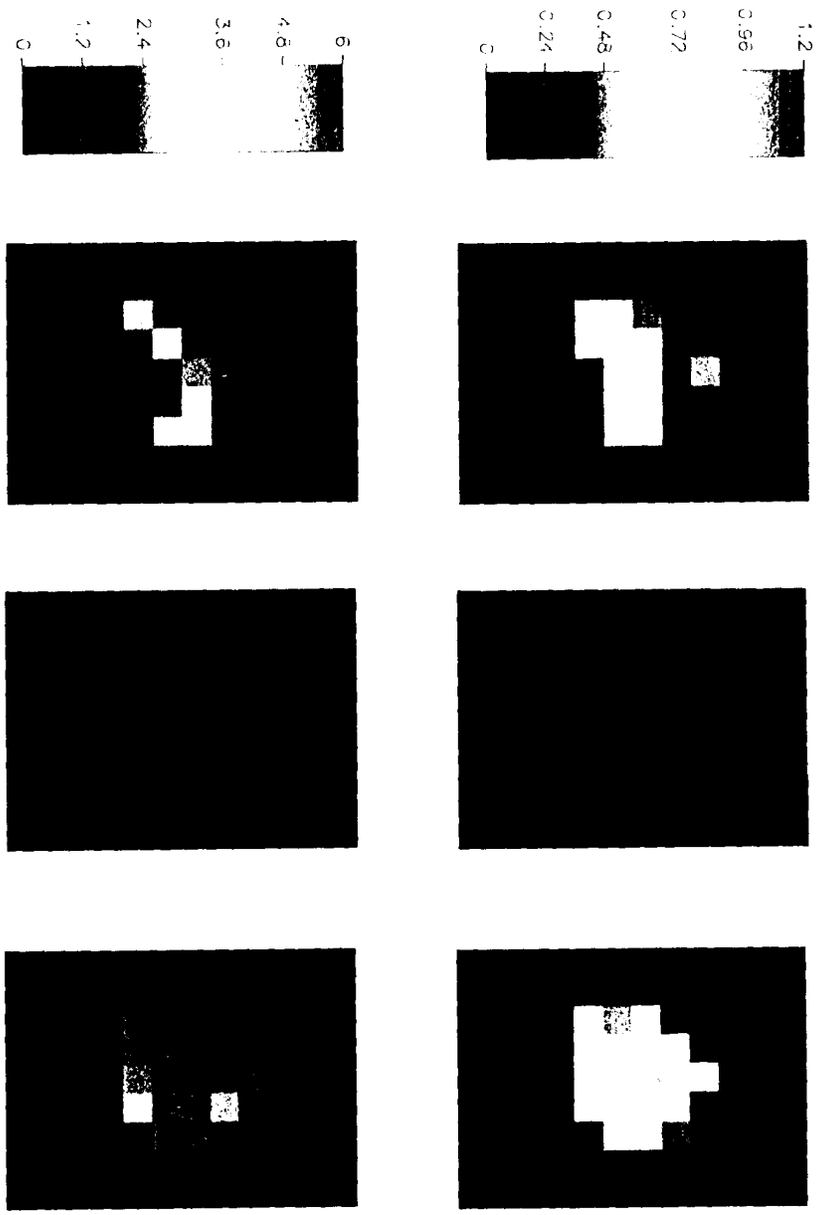

Figure 5. Maps of the extinction and optical depth in 2 1.124″ cells of NGC6916. The optical depth is shown on the left, the extinction on the right with the colour key at the top of each column. The top maps show the best fitting results, the middle maps show the lowest results that could be consistent with the data and the bottom maps show the highest results that could be consisitent with the data.

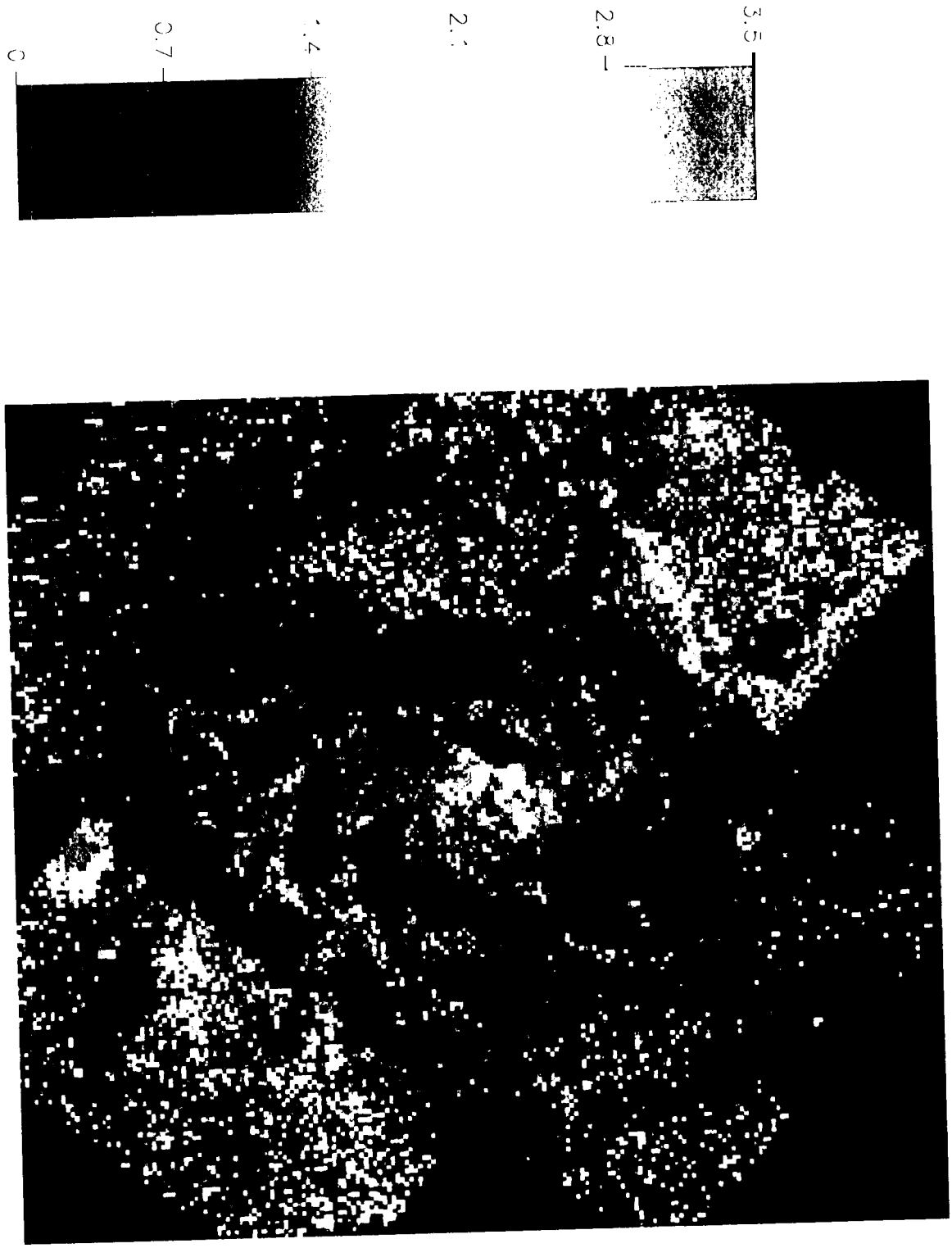

Figure 4. Extinction map of NGC 6946. The B band extinction (A_B) is shown in magnitudes as indicated by the scale

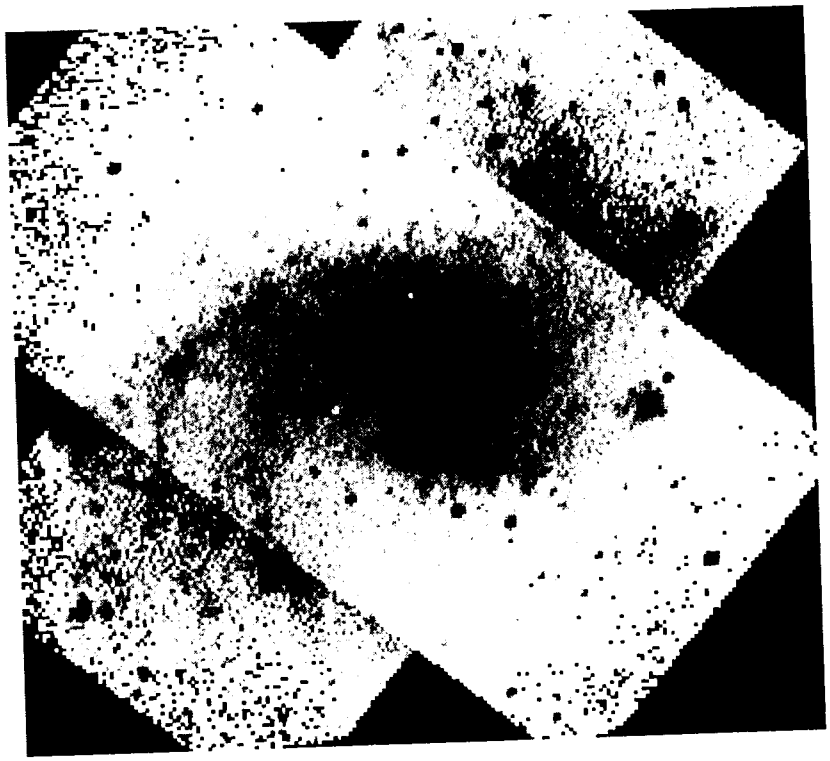

Figure 5. Reconstructed B band image of NGC 6946. The image is shown at the same size, orientation and linear intensity scale as the observed B band image, figure 2.