Chapter 5

Features in early-type galaxies

5.1 Introduction

According to the classical view, elliptical galaxies are considered to be nearly free of dust, gas or any other form of substructures e.g. faint disk within them. In the classification scheme of galaxies introduced by Hubble, any galaxy showing presence of dust and/or disk were put under a separate class of lenticulars. The Centaurus A (NGC 5128), a well known nearby radio galaxy was considered to be the only elliptical known to contain a prominent dust lane visible in direct images. However, Hubble (1930) himself had reported presence of dust patches in some of the classical ellipticals. In the later part of photographic era of astronomical observations the number of ellipticals possessing dust feature increased, which blurred the distinction between the rotationally supported, dusty, disky lenticular galaxies and the anisotropic pressure supported ellipticals containing a significant amount of inter-stellar matter (ISM).

With the aid of powerful imaging detectors, the CCDs along with fast and efficient image reduction techniques, the number of genuine ellipticals having dust and gas in various forms has increased considerably. From ground based optical observations Sadler & Gerhard (1985) had shown that ~40% of ellipticals contain significant amount of dust. The true fraction of ellipticals containing dust in a sample of elliptical galaxies studied by Goudfrooij et al. (1994b) is as high as ~80%, almost same as that reported by van Dokkum & Franx (1995) ~78% ± 16.

Malin & Carter (1983) reported that many early-type galaxies possess faint arc-like brightness enhancement, known as shells or ripples. These features can be
explained in terms of accretion of companion galaxies (Hernquist & Quinn 1988; Thomson 1991) or major mergers of spiral galaxies. Hernquist and coworkers (Barnes & Hernquist 1992; Hernquist & Spergel 1992) found a large fraction of ellipticals and lenticulars to have these ripples or shell-like structures in them. Furthermore, Carter (1987) had shown that some rapidly rotating ellipticals contain weak stellar disks, which implied that such disk may be common components in rapidly rotating ellipticals.

Isophotes of early-type galaxies are well represented by nearly perfect ellipses. However, observations with CCD detectors have revealed that the isophotes show very small but significant deviation $\sim 1-2\%$ from the pure ellipses. These deviations from pure ellipses indicate presence of some non-elliptical features in them. The non-elliptical faint features seen in these galaxies bear special significance in understanding various processes operating in galaxies during their formation and subsequent evolution.

Among the different phases of ISM, initially the dust received considerable attention as it was found to be very important in determining the intrinsic shape of these galaxies (van Albada et al. 1982). The orientation of dust disk along major, minor or intermediate axes provides clue as regards the true figure of galaxies, which may be oblate, prolate or triaxial systems. Further, the dust is found to be kinematically decoupled from the stellar body of the galaxy, which led to the suggestion that dust has an external origin, accreted from outside the galaxy through various mechanisms.

The presence of fine structures in the form of dust, shells, ripples x-structures, plumes, jets, stellar disk, boxiness of isophotes etc. are supposed to be signatures of merger and/or interaction between galaxies. Seitzer & Schweizer (1990) and Schweizer & Seitzer (1992) have defined a fine structure parameter, which primarily measures the amount of fine structures in a galaxy. This fine structure parameter is found to correlate with the spectral line strength and luminosity in the sense that ellipticals with much fine structures are more luminous, and have stronger than average H$_\beta$ absorption and weaker than average CN and Mg$_2$ features for their luminosities. Further, fine structure parameter is also found to increase with increasing blue global galaxy colour (Schweizer & Seitzer 1992). These facts suggest that ellipticals with much fine structures have experienced more recent, and perhaps more gas rich mergers, which enhanced star formation in them as compared to their featureless counterparts. These young population of stars have strengthened the Balmer absorption
features and diluted the CN & Mg absorption features. Looking into the importance of these features in the formation and subsequent evolution of these galaxies we have made detailed investigation of faint features in some early-type galaxies, for which optical & NIR photometry is given in Chapters 3 & 4, respectively. This work has led to detection of new features in several galaxies of the sample.

5.2 Feature detection techniques

If we assume that isophotes of ellipticals and lenticulars are characterized by perfect ellipses, any significant deviation of isophotes from pure ellipses may be regarded as an indicator of the presence of some faint features in them. However, these isophotal distortions and features which possibly is responsible for the deviation are usually too small to be discernible in direct images of galaxies. Very high quality data obtained under very good seeing conditions and sophisticated image processing techniques are, therefore, needed for the purpose of detection. The problem of detecting and enhancing faint structures such as, dust lane/patch, shells, faint stellar disk in galaxies is not new. A variety of image processing techniques have been used for the detection of fine structures otherwise hidden in the overall signal of the galaxy (Sahu et al. 1996b, and references therein). Recently, Abans & Abans (1998) have made use of image enhancement by transform processing for the detection of fine structures in direct CCD images of galaxies. In the following we briefly describe various techniques usually employed for the detection of faint features in galaxies.

- **Inspection of direct images**: The strong absorption features, mainly caused due to the presence of dust may be seen in the direct images taken at shorter wavelengths (usually B band), if the dust is in the form of a disk and viewed almost edge on. Sadler & Gerhard (1985) have detected dust in several early-type galaxies by careful examination of B band images.

- **Quotient image**: The visibility of the faint features can be increased by dividing galaxy image with its smooth model. A model image of galaxy is generated from the linear interpolation of best fitted ellipses. This model image is expected to be a faithful reproduction of surface brightness, ellipticity & position angle profiles of the original image, and additionally it is free from noise. Absence of non-elliptical features in the galaxy will therefore, give us average value of unity for the entire quotient image. In the portion of image containing some
absorption features like dust, the quotient image will have values smaller than unity, whereas in the case of some emission features it will have values more than unity. The quotient image technique is found to work well in the regions near the center, where the relative effects of shot noise on fixed intensities are small. Lauer (1985) and Ebneter et al. (1988) have used this method for detection of dust and other faint structures in early-type galaxies. This technique has also been applied by van Dokkum & Franx (1995) on the IIST images for revealing faint features.

- **Residual image**: This method differs slightly from the quotient image technique. In this technique a smooth model of the galaxy is subtracted from the galaxy image in the same passband, and is found to work well for the search of fine structures in the outer envelopes but not near the center, where the absolute contribution of the shot noise is large (Lauer 1985).

- **Colour-index image**: The technique is the most direct and widely used technique to discern the dust features using broad band imaging. Colour-index map of a galaxy is obtained by dividing the direct image of galaxy in two widely separated filters and converting it into the magnitude scale. Several investigators e.g. Veron-Cetty & Veron (1988), Singh et al. (1994), Sahu et al. (1996b) have used this method for the detection of dust features in early-type galaxies. Sparks et al. (1985) have proposed and modified colour-index technique, in which instead of direct images of galaxy in two filters, model image of the galaxy having perfect elliptical isophotes in the longer wave band filter is used. This method is superior to the direct colour-index technique as the noise in the colour image is introduced through only one image and distortions of the isophotes by dust is minimized in the model image at longer wavelength. However, the seeing PSF in the images in two filters should be made equal before constructing colour-index images, otherwise seeing difference may cause pseudo colour enhancement in the galaxy, specially near the center.

- **Unsharp masking**: It is a powerful technique allowing spectacular enhancement to the faint features of an image. In this method the image is first smoothed by a low pass filter (i.e. averaged locally) and a mask is created. This mask is then subtracted from the original image. Malin & Carter (1983) have used this method for detection of shells or ripples in photographic images of several galaxies. Seitzer & Schweizer (1990) have used this method for the search of fine structures in direct CCD images of galaxies.
• **Residual image with clipping algorithm**: This technique is a variant of the model image subtraction as described earlier with slight modifications. The non-elliptical features deviates the isophotes from pure ellipses. The modeling algorithm samples all the points including the features present, if any, while generating model of these galaxies, and thus the residual image (galaxy-model) will be free from the features. In the clipping algorithm a certain fraction (up to 40%) of the bright pixels at each isophotal radii is clipped off during the ellipse fitting process, and hence model is the smooth representation of the galaxy. The residual image then reveals the non-elliptical feature present in the galaxy more prominently, than can be seen from the simple residual image obtained without clipping. This method is best suited for detecting the bright features e.g. shells or ripples. Forbes & Thomson (1992) has used this technique for detecting bright features in elliptical galaxies, and usually the images in longer wavelengths e.g. R-band are used for this purpose.

5.3 Results and discussion

We have considered all the galaxies observed by us as a part of the present work for which detailed surface photometric analysis has been presented in Chapters 3 & 4, for the purpose of examining the presence of features in them. For this purpose we have used the detection techniques described in the previous section. Here, we give comments on individual galaxies in which the presence of dust or other form of fine structures in them were detected. This includes new detections as well as confirmation of previously known features.

5.3.1 Features in individual galaxies

• **NGC 16**: NGC 16 is a barred lenticular galaxy of SBO type, having a very faint interacting pair. The faint bar present in this galaxy is almost perpendicular to its major axis. B-R Colour image of the galaxy shows red feature near the center, which looks like spiral arm originating from the center and is found to be extended only in one direction. IRAS data gives only upper limits for this galaxy (Table 5.1). The effects of the presence of the bar is clearly seen in the profiles of ellipticity and position angle as well as in the $b_4$ profile. The $b_4$ is throughout pointy but its values oscillates reaching to the maximum value 0.03.
Table 5.1: Far-infrared flux (in mJy) of galaxies.

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Ellipticity and position angle profiles show abrupt change at r~5", a feature which also appears as a kink in the brightness profile. We associate this feature to the presence of weak inner bar of length ~5".

- **NGC 383**: NGC 383 is the brightest galaxy of type LA belonging to the group (chain) Arp 331. The other galaxies forming this chain are NGC 319, NGC 380, NGC 382-386. It is a radio galaxy of type FRI having two strong radio jets emerging from the nucleus (Butcher et al. 1980). Hα observations of the galaxy show only nuclear emission. It has been detected by IRAS at 60 and 100 μm (Table 5.1). This galaxy is known to have a central dust lane parallel to the optical major axis. CCD images of this galaxy taken by us, however, does not show the nuclear dust lane or any other significant feature. In the outer region the b4 and other Fourier coefficients show a tendency for non-zero values. Because of poor S/N in this region, however, it is difficult to ascertain the reality of these values.

- **NGC 656**: NGC 656 is classified as LB in RC3 with no previously published photometry. The variation in the ellipticity and position angle is due to the presence of the bar in the galaxy, the ellipticity profile and corresponding bump in the luminosity profile at ~10". According to Wozniak & Pierce (1991) this gives the actual length of the bar. From visual inspection of the contour plot of the galaxy covering the bar region, the length of the bar is estimated to be ~12", which is somewhat larger than that estimated from the luminosity and ellipticity.
profiles. The ellipticity rises from 0.1 to 0.35 in the bar region (i.e. 4-10"). The b₄ coefficient becomes significantly positive between 4-10", this again reflects the presence of the bar.

- **NGC 661**: It is a smooth ideal elliptical galaxy classified as E+ (RC3) without having any feature. It is detected by IRAS only at 100μm (Table 5.1). The colour-index map and residual image do not show any faint feature in the galaxy. Ellipticity of the initial rise reaches to a maximum of ~0.32 and then finally settles a value of ~0.30 in the outer regions. Position angle remains nearly constant throughout and the Fourier parameters do not show any significant deviations.

- **NGC 720**: It is a flattened elliptical galaxy classified as E5 (RC3). Based on its isophotal shape Nieto et al. (1994) have categorized the galaxy in the irregular class. Sparks et al. (1985) have reported a broad red nucleus in it. Hα+[NII] observations have been carried out on this galaxy by Shield (1991), Goudfrooij et al. (1994a) giving null result, while Macchetto et al. (1996) have detected Hα emission in this galaxy with a flux F_{Hα+[NII]} = 17.66 \times 10^{-14} \text{erg sec}^{-1} \text{cm}^{-2} and Hα+[NII] luminosity L_{Hα+[NII]} = 19.1 \times 10^{39} \text{erg sec}^{-1}. It is a low power radio galaxy with logP₅ (WHz) < 20.90 and a X-ray loud galaxy with log Lₓ = 41.21 \text{erg sec}^{-1} (Cannizare et al. 1987). It is marginally detected by IRAS at 12 μm only (Table 5.1). Goudfrooij et al. (1994a) have reported a weak disk along major axis and X-structures near the center. We also found a weak stellar disk along the major axis, but the presence of X-structure is not clearly seen in the residual R-band image obtained using the clipping algorithm. Except for b₄ coefficient other Fourier coefficient donot show any significant deviation. b₄ in R band however is slightly boxy over intermediate range of nuclei.

- **NGC 1052**: It is a well studied elliptical galaxy classified as E4 (RC3) with a flat radio spectrum (Diesney & Wall 1977) with radio power log P₅ (WHz) = 22.80. It contains a diffuse faint dust lane detected by Carter et al. (1983). It also contains a fairly substantial amount of inter stellar medium in all the forms i.e. ionized gas (Kim 1989), atomic gas (van Gorkam 1986) as well as X-ray emitting hot coronal gas. Atomic gas in this galaxy has been detected in the form of a rotating disk lying perpendicular to the major axis of the stellar body. Ionized gas is confined to its inner 10", with flux F_{Hα+NII} = 8.1 \times 10^{-13} \text{erg sec}^{-1} \text{cm}^{-2}. It is considered to be a case of merger remnant. The X-ray luminosity is consistent with a hot gaseous halo in which a cooling flow is claimed to be
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Figure 5.2: Residual image of NGC 720 showing stellar disk along the major axis

Figure 5.3: Colour index image of NGC 1052 showing filamentary dust in the center

operating (Thomas et al. 1986). A double gaseous component has recently been discovered in the object. (Plana et al. 1998). It is a strong IRAS source (Table 5.1). Our optical data also reveals the dust lane in it. The $b_4$ is negative with a maximum of $\sim$ -0.02 within about 20" beyond which it is slightly pointy.

- **NGC 1199**: It is an elliptical galaxy of type E3 (RC3) known to have a dust ring (Sparks et al. 1985) which is symmetric about major axis. Veron-cetty & Veron (1988) have also detected the dust feature. Appletone et al. (1985) have found neutral hydrogen in emission which is associated with its nearby companion galaxy MCG 08-08-61. Only upper limits of FIR fluxes are available from IRAS (Table 5.1). The colour-index maps in B-R & B-K$'$ obtained by us
confirm the presence of dust ring crossing the stellar body of the galaxy near the nucleus. Profiles for structural parameters of this galaxy show that $b_4$ is negative with marginal colour dependence within 10". In the same region ellipticity profile also shows wavelength dependence. This feature may be associated with the dust ring of the galaxy.

- **NGC 1201**: This galaxy has been classified as LAR0 in the RC3 catalogue. Roberts & Sandage (1993) have classified it as SO1(P)- dust free SO galaxy with pronounced envelope. Only upper limits on FIR fluxes are available (Table 5.1). A careful examination of our $K'$-band direct image of this galaxy shows the presence of a faint bar like structure in the inner region having a size of ~ 18" as evident from the contour plots of this region. The presence of this substructure can also be seen from the shapes of ellipticity as well as position angle profiles. $b_4$ coefficient is significantly positive in the interior 10" which may be associated to the presence of inner bar.

- **NGC 1587/88**: NGC 1587/88 form an interacting pair (Ep+Ep) with a projected separation of 12Kpc. It is a weak radio source. It shows weak FIR emission at 12μm (Table 5.1). Gallagher et al. (1981) have reported a possible detection of HII, but this could not be confirmed from later observations with more sensitive detectors. Borne & Hoessel (1988) have made a detailed modeling of this pair. They found that NGC 1587 is one of the highest rotating elliptical with a value of $v/σ = 0.6$. Because of the fact that the rotation is in the same sense...
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Figure 5.5: (a) Residual image of NGC 1201 showing shell-like structure along major axis, and (b) elongation in the isophotes indicating the presence of a bar.

as that of the binary orbital motion, the net angular momentum of this pair is large, which challenges a simple tidal torque to be the source of momentum. It is possible that NGC 1587 is itself a merger remnant with its spin being a relic of the orbital angular momentum in its previous binary interaction. The asymmetric distortions in the isophotes in the significant portion of the pair is seen. The outer isophotes of each galaxies is found to be displaced with respect to the inner ones in the opposite sense along a direction which is nearly perpendicular to the line joining the centers of the two galaxies. Colour index image of this galaxy is featureless. The residual image of NGC 1587 shows shell like features which are believed to be one of the important signatures of the merger process. This provides additional support for it to be called a merger remnant. The optical structure of NGC 1588 is very disturbed and therefore, we did not make any attempt in search for features in its residual or colour map. Fourier $b_4$ coefficient is slightly positive in the intermediate range of radii for the case of NGC 1587, while NGC 1588 has significantly negative $b_4$ coefficient at $\sim 10''$.

- **NGC 1600**: It is a low power radio galaxy classified as E3 (RC3) with boxy isophote (Nieto et al. 1984). It shows extraordinarily little rotation along either axis (Jedrzejewski & Schechter 1989). It is known to be a cooling flow and
X-ray loud galaxy with X-ray luminosity $\log L_X = 41.65$ ergs$^{-1}$ (Forman et al. 1985). This galaxy is marginally detected in $\Pi_\alpha+\text{[NII]}$ emission (Trincheri et al. 1991) with $\Pi_\alpha+\text{[NII]}$ flux $\lambda \mu_a = 7.23 \times 10^{40}$ erg sec$^{-1}$; $\Pi_\alpha+\text{[NII]}$ emission was later confirmed by Singh et al. (1995). It has been detected by IRAS at 60 and 100 $\mu$m (Table 5.1). (Forbes et al. 1994, 95) have detected a secondary nuclei in this galaxy, which is believed to be a signature of merger process. The residual R-band image of this galaxy obtained using the clipped model shows the presence of X-structure in the central region. The inner boxy isophotes that this galaxy has is attributed to the observed X-structure.

- **NGC 1653**: It is an elliptical galaxy with no previous detailed photometric studies available. The application of all the techniques for search of features resulted in null detection. $b_4$ is positive within the radius of 10$''$. 

- **NGC 1993**: This is a lenticular galaxy of type LAT (RC3) having no previous photometric study. The colour index as well as the residual image does not reveal presence of any structure. The Fourier coefficient $b_4$ does not show non-zero value at significant level.

- **NGC 2076**: This is lenticular galaxy classified as L+ known to have prominent dust lane nearly along the major axis (Ebneter & Balick 1985), its dust configuration has been categorized as oblate. The low resolution map of this galaxy shows an extended source of radio emission, however, the high resolution map of this galaxy practically shows nothing (Mollenhoff et al. 1992). It is strong IRAS
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Figure 5.7: B-R colour index image of NGC 2076, darker region corresponds to the area covered by dust lane.

source (Table 5.1). A detailed study of dust properties in this galaxy has been given in the next section.

- **NGC 2110**: This is an active galaxy, classified as LX in RC3. It is a powerful X-ray galaxy with the optical emission much narrower than permitted lines of type 1 Seyfert galaxy. Its active nature was discovered through X-ray observations by Bradt et al. (1978), who noted that the optical object appears like an elliptical galaxy. It is also a moderately strong radio source. The radio mapping of this galaxy show a linear jet like radio structure associated with the nucleus (Ulvestad & Wilson 1983). It has also been detected by IRAS (Table 5.1). Our colour index image of this galaxy shows dusty ring very close to the nucleus. This dusty ring alongwith the other forms of ISM present in the galaxy is supposed to play a vital role in the formation of the nuclear radio source (Ulvestad & Wilson 1983). HST image of NGC 2110 also reveals dusty spiral disk in the nuclear region (van Dokkum & Franx 1995). The $b_4$ profile does not reveal any pointy or boxy isophote. $b_3$ and $b_3$ however, have non-zero values in the inner region occupied by the dusty spiral disk and ellipticity and position angle profiles show a significant wavelength dependence in this region.

- **NGC 2274**: This is an elliptical galaxy belonging a local group of galaxies No. 139. The other members of this group are NGC 2275, NGC 2290, UGC 3537. It forms a mixed E+S pair with NGC 2275 at a projected distance of $1'$.93 and velocity difference of 144 kms$^{-1}$. Only upper limits on FIR fluxes are
The colour index images of this galaxy both in B-V and V-R show a dusty patch, asymmetrical about the center. The residual image of this galaxy using the clipping algorithm shows diffuse shell-like feature in this galaxy, presumably caused by an ongoing interaction of galaxy NGC 2274 with its companion NGC 2275. The $b_4$ profile shows slightly positive values in the outer region which may be associated with the detection of diffuse shell-like structure in the galaxy. The ellipticity profile and position angle profiles exhibit colour dependence, as is expected in dusty region. The $a_3$ or $b_3$, however, do not have significant non-zero values.

- **NGC 2476**: This is an elliptical galaxy known to have inner pointy and outer boxy isophotes (Forbes & Thomson 1992). These authors have detected shells along with a box or X-structure in this galaxy. Our results showing the residual image of the galaxy in the R-band obtained with clipping algorithm also shows these faint structures, which may be associated to the non-zero values of $b_4$. Colour-index maps of this galaxy, however, are featureless.

- **NGC 2513**: It is a very smooth elliptical galaxy known to have minor axis rotation (Jedrzejewski & Schechter 1989). The colour and residual maps of this galaxy practically show nothing. The profiles of higher order coefficients do not show any significant deviation from those of pure ellipse.

- **NGC 2954**: It is a radio quiet galaxy classified as elliptical (Heckman et al. 1985). Haynes & Giovanelli (1984) have quoted possible detection of HI with
Figure 5.9: B-R colour index image (a) and R band residual image (b) of NGC 2274, revealing the patchy dust and diffuse shells, respectively.

Figure 5.10: Residual image of NGC 2476 showing shells.
very uncertain parameters. Only upper limits on FIR fluxes are available (Table 5.1). The B-R colour index image of this galaxy shows an extended red region surrounding the nucleus. The residual image of this galaxy shows X-structure in the central region of the galaxy. The $b_4$ coefficient shows positive value throughout the range of radii, which may be associated with the X-structure detected in it.

• NGC 3497 : This is a lenticular galaxy of type LASO (RC3) having a dust disk along the major axis of the galaxy (Ebneter & Balick 1985). The dust lane crosses the stellar body in a ring like structure. The colour index image of this galaxy clearly shows dusty ring around the stellar body of the galaxy. FIR data not available. We have studied the dust properties of this galaxy and is described in detail in the next section. Apart from the prominent dust ring no other fine structures were detected in this galaxy. This galaxy has positive values of $b_4$ with large error bars in the outer region.

• NGC 4374 : It is a well studied elliptical galaxy with skewed dust lane. Lauer (1985) have shown it to have boxy isophotes. It is a classical cooling flow double lobe radio galaxy with X-ray emission from its surrounding halo having the mass of coronal gas $= 7.34 \times 10^8 M_\odot$. (Forman et al. 1985). Its $H_\alpha+[NII]$ emission is well aligned with the dust lane and extended on both sides of the nucleus (Baum et al. 1988). The dust lane is oriented almost perpendicular to the radio

Figure 5.11: B-R colour index image (a) and R band residual image (b) of NGC 2954, revealing the red elongated nucleus and bright X-feature along major axis, respectively.
Figure 5.12: V-R colour index image of NGC 3497 showing dust ring around the center.

jet. The Hα+[NII] luminosity \( L_{H\alpha+[NII]} \sim 3.6\times10^{39} \) ergs. It is a strong IRAS source (Table 5.1). The HST image of this galaxy shows a complicated dust lane projected against the nucleus, which looks like a small wrapped disk. Such features eventually settle into a principal plane of triaxial potential and reach an equilibrium configuration (Jaffe et al. 1994). Among the higher order coefficients for this galaxy \( a_3 \) and \( b_3 \) have significantly non-zero values in the central region occupied by the dust lane, while the negative values of \( b_4 \) confirms it to be have boxy isophotes.

- **NGC 4564**: NGC 4564 is a flattened elliptical galaxy showing a clear photometric evidence of bulge disk segregation. (Nieto et al. 1994) have categorized this as a disky galaxy. Michal and Marchal (1994) have suggested that it might very well be classified as SA0. Goudfrooij et al. (1994a) have reported it to have a fairly prominent stellar disk along major axis. The narrow band imaging of this galaxy by Goudfrooij (1994b) shows Hα+[NII] emission in the nucleus. The HST image of this galaxy reveals that it contains very faint patches of dust (Jaffe et al. 1994). Only upper limits on FIR fluxes are available (Table 5.1). Our colour index image does not show any feature in this galaxy, however. The residual image shows a prominent stellar disk in the galaxy having similar in colour to the underlying spheroidal component because the colour-index map B-R does not show any colour excess. The detailed properties of the stellar disk is discussed separately in the next section.
Figure 5.13: B-R colour index image of NGC 4374 showing the dust lane.

- **NGC 5813**: Sparks et al. (1985) have noticed a red patchy region near the center of this galaxy, while Veron-Cetty & Veron (1988) have noticed off-nuclear dust filament in it. This galaxy shows large gradients in $Mg_2$ and visual-infrared colours with almost constant optical colours. Not an IRAS source; only upper limits on FIR fluxes are available (Table 5.1). It shows rapid stellar rotation with two concentric cores having properties of low and high luminosity ellipticals (Efstathiou et al. 1982). This led to the suggestion that it is a merger remnant (Kormendy 1984). Peletier (1990a) and Goudfrooij et al. (1994b) noticed a patchy dust close to the center. Further, this galaxy is found to emit in $H_\alpha+[NII]$ with $H_\alpha+[NII]$ luminosity $L_{H_\alpha+[NII]} \times 10^{39}$ erg s$^{-1}$. The $H_\alpha+[NII]$ distribution is extended and its morphology is not at all related with the stellar body of the galaxy.

- **NGC 5846**: This galaxy forms an interacting pair with NGC 5846A having a redshift difference of 527 kms$^{-1}$. It is an X-ray loud galaxy with luminosity $logL_X = 41.94$ (Canizares et al. 1987) and a weak radio galaxy having off nuclear dust filaments. Only upper limits on FIR fluxes are available (Table 5.1). Complex line emission centered on the nucleus with a radial filamentary structure has also been noticed in this galaxy (Trincheieri et al. 1991). A combination of high resolution X-ray images from ROSAT with those in optical broad band and $H_\alpha+[NII]$ shows that X-ray emission, nebular emission and dust have strikingly similar morphology, implying a physical connection between various form of ISM.
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Figure 5.14: R band residual image (a) and B-R colour image (b) of NGC 5813; faint extended X-structure is seen in the residual image and a red patch near the center is seen in the colour image.

in this galaxy (Goudfrooij & Trinchieri 1998). The residual image of this galaxy in the R-band shows a bright shell-like structure close to the nuclear region. However, B-R colour-index image turns out to be featureless. We could not confirm the filamentary dust detected by Goudfrooij & Trinchieri (1998), perhaps due to very poor seeing.

- **NGC 6758**: This is an elliptical galaxy classified as E2, with low radio emission. Sparks et al. (1985) have noticed a red nucleus 0.1m redder than the body of the galaxy. It has been detected in Hα+[NII] emission having luminosity L_{Hα+[NII]} of $28.2\times10^{39}$ erg s$^{-1}$ (Macchetto et al. 1996). Marginally detected by IRAS (Table 5.1). The B-R colour index image of this galaxy shows a central red nucleus. An arm like structure is also seen in the central portion of the galaxy. The $b_4$ and other Fourier coefficients are almost zero throughout the range of radii.

- **NGC 6776**: This is an elliptical galaxy classified as E+ in RC3. It is a radio and x-ray quiet galaxy. Malin and Carter (1983) have reported a shell or loop like structure near to the center. It has been detected in Hα+[NII] emission having luminosity L_{Hα+[NII]} of $73.8\times10^{39}$ erg s$^{-1}$ (Macchetto et al. 1996). It has been detected by IRAS at 60 and 100 μm (Table 5.1). Our B-R colour index image of this galaxy shows a red elongated region (i.e. dust) close to its nucleus. The residual image of the galaxy in R-band obtained with the clipped model however does not show any feature in this galaxy. The $b_4$ coefficient is negative around 10$''$. 
Figure 5.15: R band residual image of NGC 5846 showing shell-like structure.

Figure 5.16: B-K' colour image of NGC 6758 showing dusty nucleus and arm-like structure.
Results and discussion

NGC 6868: It is a very interesting elliptical galaxy of type E3 belonging to the group GR2. Sparks et al. (1985) have observed a red nucleus, while Sadler & Gerhard (1985) have noted the presence of dust in this galaxy. Veron-Cetty & Veron (1988) have shown it to contain dusty nuclear region with dust content of \( \sim 0.4 \times 10^5 M_\odot \). Huchtmeyer et al. (1992) have quoted as upper limit of neutral hydrogen mass \( \sim 0.56 \times 10^{10} M_\odot \). It is also known to host a radio source. Detected by IRAS at 60 and 100 \( \mu \)m (Table 5.1). The central dust lane is associated with ionized gas observed in \( H_\alpha + [NII] \) and \( I_{[Ly}\alpha} \). It also harbours a weak UV continuum source, which is considered as the ionizing source of line emitting cloud (Hansen et al. 1991) which led them to suggest that it has recently captured a gas rich galaxy. The captured galaxy may be the source of central activity. This view has been strengthened by Buson et al. (1993) who showed that the velocity field and the velocity dispersion profiles of the ionized gas are symmetrical about the center. The gas does not move in regular orbits, which is taken as an evidence for a distinct counter rotating gas component. The colour-index images in B-R as well as in B-K' of this galaxy show nuclear dust in the form of a redder disk, having a spiral arm like feature extended only in one direction of the center. This feature is more prominently seen in the optical-NIR (positive B-K') colour map of the galaxy, because of the broad base line in the wavelength in B-K' colour and also due to the reason that dust extinction is very small in the K'-band. The \( b_4 \) coefficient is marginally pointy in the outer portion of the galaxy.

NGC 6958: It is a weak radio galaxy with dust in its nucleus with its nucleus 0.4m redder than the galaxy in B-I (Veron Cetty & Veron 1988). It shows a strong emission at FIR (Table 5.1). Malin and Carter (1983) have noted a distinct inner structure in it. Our image of this galaxy also shows the redder dusty region near the nucleus. The Fourier coefficient \( b_4 \) is almost zero in the inner region and quite noisy in the outer region.

NGC 7144: It is an elliptical galaxy classified as E0 in the RC3. It has been detected by IRAS at 60 and 100 \( \mu \)m (Table 5.1). The residual as well as colour image of this galaxy does not presence of any faint features. The higher order Fourier coefficients are all zero throughout the range of radii.

NGC 7562: This galaxy is the third brightest member of Pegasus 1 cluster and forms as interacting pair with NGC 7557 with a projected separation of 3'.1 and a radial velocity difference 126 km s\(^{-1}\). It shows \( H_\alpha + [NII] \) emission having a luminosity \( L_{H_\alpha+[NII]} \) of \( 7.4 \times 10^{39} \) erg s\(^{-1}\) (Macchetto et al. 1996). For FIR
Figure 5.17: B-K’ colour image (a) and R band residual image (b) of NGC 6868, showing dust disk and diffuse shells around the nucleus, respectively.

Figure 5.18: B-R colour image (a) and R band residual image (b) of NGC 6958, showing nuclear dust and diffuse shells around the center, respectively.
emission only upper limits are available (Table 5.1). The isophotal analysis shows it to have inner boxy and outer pointy isophotes; which is in good agreement with the earlier investigations. Our colour index image shows it to have nuclear dust, while residual image obtained using clipping function reveals the presence of outershells in the galaxy. A detailed analysis of this galaxy has already been given in Chapter 2.

Thus, using a variety of techniques used for the search of dust and other faint structure, we found 14 out of the 31 galaxies in our sample to have dust either in form of patch or well defined geometries. Nine galaxies were previously known to have dust, while five are the new detections from the present work. Out of 31 galaxies 9 are found to have other forms of fine structures e.g. shells, X structures etc., and out of these 7 cases are the new detections.

Out of all the higher-order terms in the Fourier expansion, the fourth-order cosine term $b_4$ has attracted the most attention. It is normally used in quantifying the isophotal distortions from pure ellipses, and hence, in classifying isophotes into boxy (negative $b_4$) or pointy (positive $b_4$). The $b_4$ values have also been found to correlate with non-morphological properties of elliptical galaxies. Further, the non-zero values of this parameter is taken as indicator of the presence of faint non-elliptical structures in the galaxy e.g. pointy isophotes are usually associated with the presence of a stellar disk embedded in the galaxy. However, depending upon the apparent orientation of the disk with respect to the local apparent major axis, it may give rise to both positive and negative $b_4$ values. In the case of NGC 7562, for example, $b_4$ is positive in the outer parts of the galaxy, and yet it does not have a stellar disk. Instead, we have shown (Chapter 2) that the presence of shells is responsible for the positive values of $b_4$ in the outer regions of the galaxy. Likewise, presence of shells or ripples oriented at an intermediate angle to the local major axis of the galaxy will give rise to boxy isophotes. Thus, there does not seem to be one-to-one correspondence between the nature of isophotal deviation, as measured by $b_4$, and the presence of fine structures causing the deviations (see also Goudfrooij et al. 1994a and Peletier et al. 1990a).

### 5.3.2 Properties of dust extinction

The interstellar matter in various forms observed in the early-type galaxies plays a significant role in understanding the formation and evolution of the underlying galaxy. The dust component of ISM has been detected in a large fraction of early-
type galaxies. Dust, which was an annoying object for the astronomers right from the beginning, has received considerable attention especially, with the emergence of infrared astronomy as an observational tool. Dust is now regarded as vital ingredients in star forming regions, and a host of other poorly understood astrophysical processes in the galactic as well as extragalactic environments. The studies on dust was initiated with a view to investigate its properties not as something worthy to study in its own right, but as a means of removing its effects from the observation of stars. Studies on dust during early 40’s was concerned mainly with the manner in which the dust obscuration varied with the wavelength in the optical region. The $\lambda^{-1}$ variation of the dust obscuration with the wavelength $\lambda$ led to identification of the obscuring material as small solid particles having a dimension of the order of optical wavelength. The investigation of dust particles in producing extinction at optical wavelengths, and in its remission at infrared wavelengths in astronomical environments is one of the most challenging and exciting areas of modern astronomy. In the sample of early-type galaxies observed by us there are few galaxies containing large scale dust with well defined morphology. We have carried our detailed investigations of the dust properties in them with a view to derive the extinction law and compare with that of our own galaxy. We have also estimated and compared the amount of dust using optical and FIR data available on these galaxies.

Extinction Curve

Early-type galaxies are suitable targets to study the dust grain properties in the extragalactic environments. The data can be used to model the size distribution of grains (Rowan-Robinson 1992), to predict the different mechanisms operating (de Jong et al. 1990; Drain & Salpeter 1979; Barlow 1978) to make the existence of dust possible in a wide variety of environments. As pointed out by Goudfrooij et al. (1994b) the physical properties of dust are a function of time and can be used as an indicator for the time elapsed since the dust was last substantially replenished. The basic tool to study the dust properties is to examine the behaviour of dust extinction in different wavebands i.e. the extinction curve. There are two main methods to determine the wavelength dependence of dust extinction in galaxies:

1. **Direct method**: This method is used to study the dust properties of our own Galaxy. The extinction curve is plotted with the help of stellar photometry of individual stars, whose intrinsic luminosity is known by means of some other
methods. Savage & Mathis (1979) and Rieke & Lebofsky (1985) have used this method to determine the behaviour of dust particles in obscuring the stellar light in our galaxy, and have derived the standard reddening law. It is further found that the Galactic extinction curve from the far infrared to the UV is mainly a function of $R_V$, the ratio of total selective extinction $A_V$ in V band to the selective extinction $E_{B-V}$ between B and V bands. The value of $R_V$ for our galaxy was found to be 3.1.

2. **Indirect method**: In extragalactic objects photometry of individual stars is not possible and hence indirect methods for calculating $R_V$ are used. Comparison between the original galaxy (extinguished) and a smooth model (unextinguished) gives an estimate of extinction by dust; this exercise at a number of wavelengths gives the extinction law. Several workers have used these indirect methods and determined values of $R_V$ for spiral galaxies (Knapen et al. 1991; Walterbos & Kennicutt 1988) quite similar to that in our Galaxy. On the other hand the values of $R_V$ for early-type galaxies are generally found to be smaller than the Galactic value (Goudfrooij et al. 1994c).

We have made an attempt to derive the extinction curve for the dusty galaxies, namely, NGC 1052, NGC 2076, NGC 3497 and NGC 4374, for which we had observations in more than two bands other than R.

**Generation of extinction map**

As discussed earlier the variation of extinction with wavelength, or $R_V$, is the basic parameter which determines obscuring properties of the dust. For the calculation of the value of $R_V$, magnitudes of extinction in different passbands are required. The amount of extinction caused by the dust present in a galaxy is determined by comparing the actual light distribution collected from the galaxy with that expected in the absence of dust. In the case of prominent dust lane galaxies with dust lane distributed asymmetrically with respect to the center, the amount of extinction is determined using the assumption that the stellar light distribution is symmetrical with respect to the nucleus. In another widely used method, isophotes of elliptical galaxies are considered to be intrinsically elliptical (Norgaard et al. 1993) and deviation present, if any, is due to features that include dust as well as other features. A smooth model of the galaxy having perfectly elliptical isophotes is obtained using the isophotal parameters generated by the ellipse fitting process. While fitting ellipses the region occupied by
dust and foreground stars are masked and ignored during ellipse fit. Now, by applying a polynomial fit to the fitted data a smooth model of the galaxy is generated. This model is used to make the first order extinction map from which the portion significantly distorted by dust is identified and flagged in the next stage of ellipse fitting to generate the smooth model of the galaxy. The model images are used to get the extinction map at each wavelength and is given by the following expression.

$$A_\lambda = -2.5 \log \left( \frac{I_{\lambda,\text{obs}}}{I_{\lambda,\text{model}}} \right),$$

(5.1)

where, $I$ stands for the ADU counts. This gives the desired extinction map in magnitude scale.

**Extinction curve**

The extinction maps in different filter were used to determine the extinction due to the dust lane. We chose a rectangular box of size three times the seeing disk, and slid it over the whole region covered by dust to determine the numerical values of local extinction $A_\lambda = B, V, R, I$. The local colour-excess or selective extinction were also calculated using the relation

$$E(\lambda - V) = A_\lambda - A_V$$

(5.2)

For determining the ratio of total to selective extinction we have used the method discussed by Brosch et al. (1990) and Goudfrooij et al. (1994c). Linear regression between the different extinction values are calculated and the best fitting slopes are assigned to be the average of the slope of $A_X$ Vs. $A_Y$ and the reciprocal slope of $A_Y$ and $A_X$. The slope of regression represents the relation between extinction at the two spectral bands. These values are used to derive the average extinction curves for the area covered by dust.

The value of $R_V$, i.e. the ratio of total extinction $A_V$ in the V band to the selective extinction $E_{B-V}$ between B and V bands, is estimated for all the four galaxies and are given in the Table 5.3, whereas its galactic value is reported as 3.1 (Savage & Mathis 1979; Rieke & Lebofsky 1985). The smaller values of $R_v$ for all the four galaxies as compared to that of our Galaxy show that the average dust particle size in these galaxies is smaller than in our Galaxy. Goudfrooij et al. (1994c) have shown that the dust particles appear larger because of foreground light and/or forward scattering, implying that the dust particle size in these galaxies is indeed smaller than in our
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Galaxy. The extinction curve for these galaxies is plotted along with the Galactic extinction curve in Figure 5.19. The extinction curve of these galaxies run almost parallel to the Galactic extinction curve which show that the properties of dust in these galaxies are similar to those in our Galaxy.

Using the extinction curve and extinction efficiency $Q_{ext}$ of spherical dielectric grains (Greenberg 1968), we have tried to estimate the relative dust grain size responsible for extinction. From Figure 5.19, it is obvious that the extinction curve varies linearly with the inverse wavelength in the optical part of the spectrum, which is also consistent with the prediction that for small grain size $x < 1$, $Q_{ext} \propto \lambda^{-1}$, where $x = \frac{2 \pi a}{\lambda}$ is the grain size in dimensionless parameters and $a$ is the grain radius. The shift of extinction curve along the increasing value of $\lambda^{-1}$ for a fixed value of $Q_{ext}$ essentially indicates the decrease in characteristic particle size $a$. The relative grain size $\langle a \rangle / a_{Gal}$ (where $a_{Gal}$ is the characteristic grain size of dust in our Galaxy) is obtained by shifting the extinction curve along $1/\lambda$ axis until it best matches with the Galactic curve. The relative grain sizes thus obtained for these galaxies are given in the Table 5.3.

For all the four galaxies the value of $R_V$ turns out to be smaller than its canonical value of 3.1 for the Milky Way, implying that the size of dust grains causing extinction is smaller than that in our Galaxy. This result is in agreement with the result obtained by Goudfrooij et al. (1991c) for a sample of 10 elliptical galaxies containing large scale dust.

5.3.3 Dust mass estimation

Dust content in galaxies may be estimated using optical colour excess, total extinction values and far-infrared flux. A brief description of each of these methods is given below.

(i) Dust mass estimation from colour-excess: As explained in Section 5.2 the dust features are identified by looking for redder features in the colour-index maps. The colour excess, under reasonable assumptions for properties of dust in early-type galaxies to be similar to that of our galaxy, can be transformed to the neutral hydrogen column density using the relation:

$$N(\text{HI}) = 5.8 \times 10^{21} E_{(B-V)} \text{ atom cm}^{-2}$$

The neutral hydrogen column density integrated over the dusty region gives an estimate of total HI content of the galaxy. Further, with an assumption that the gas-to-
Figure 5.19: Extinction curves.
mass ratio in ellipticals is similar to that of the galactic value the total dust content of the galaxy can be estimated. The colour excess other than \( E(B-V) \) is transferred, wherever needed, to \( E(B-V) \) with the help of the standard reddening curve of our galaxy (Savage & Mathis 1979). It is a very general and most widely used method for the estimation of dust mass. Due to lack of sufficient data of HI observation in E&SO galaxies the gas-to-dust ratio in them could not be determined accurately and therefore, it is taken to be the same as that in Milky Way, which may not be true. The dust masses computed using this method for the galaxies with detectable dust are given in the Table 5.2.

(ii) Dust mass from total extinction value: An alternative method of determining the mass of dust in the galaxies with a large scale dust is from optical extinction values. The extinction values determined in the extinction map of the galaxies is used for this purpose. A given grain size distribution function \( n(a) \) of spherical particles with extinction efficiency \( Q_{ext}(a, \lambda) \) at wavelength \( \lambda \) and the cut-off grain size as \( a_- \) and \( a_+ \), provides the cross section for optical extinction at wavelength \( \lambda \) as

\[
C_{ext}(\lambda) = \int_{a_-}^{a_+} Q_{ext}(a, \lambda) \pi a^2 n(a) da
\]  

(5.4)

The total extinction \( A_\lambda \) at wavelength \( \lambda \) due to dust column of length \( l_d \) is given by

\[
A_\lambda = 1.086 C_{ext}(\lambda) l_d
\]  

(5.5)

Further, the dust mass column density \( \Sigma_d \) can be calculated with the help of \( \rho_d \), specific grain mass density as :

\[
\Sigma_d = \int \frac{4}{3} \pi a^3 \rho_d n(a) da \times l_d
\]  

(5.6)

There are several models with varying chemical composition and size distribution to reproduce the galactic extinction curve. The chemical composition of silicate and graphite grains is considered to be the best one in fitting the galactic extinction curve in the optical and IR part very well. Out of the various models the model given by Mathis et al. (1977) is a better choice. According to this the size distribution of dust particles is given by

\[
n(a) = n_0 a^{-3.5} (a_- \leq a \leq a_+).
\]  

(5.7)

The upper and lower dust particle sizes are taken to be \( a_+ = (a > / a_{Gal}) \times 0.22 \) \( \mu m \) and \( a_- = 0.005 \mu m \) where \( a > / a_{Gal} \) is the relative grain size of dust and \( a_{Gal} \)
is the characteristic grain size of dust in our galaxy. The values of \( <a>/a_{silicate} \) are obtained by shifting the extinction curve along the 1/\( \lambda \) axis until it best matches with the galactic curve. The relative sizes of dust grains for the four galaxies are given in Table 5.3.

Extinction efficiencies are taken from literature and can be expressed as

\[
Q_{ext\ silicate} = 0.8a/a_{silicate} \quad for \quad a < a_{silicate} \\
= 0.8 \quad for \quad a \geq a_{silicate} \\
Q_{ext\ graphite} = 2.0a/a_{graphite} \quad for \quad a < a_{graphite} \\
= 2.0 \quad for \quad a \geq a_{graphite}
\]

where \( a_{silicate} = 0.1 \mu m \) and \( a_{graphite} = 0.05 \mu m \) (Goudfrooij et al. 1994c). The dust mass estimated using this method is given in Table 5.3.

(iii) Dust mass from FIR flux: The dust mass can also be calculated using the IRAS flux densities at 60 \( \mu m \) and 100 \( \mu m \), using the formula by Bothun et al. (1989)

\[
M_d = 5 \times D^2S_{100}[exp(144/T_d - 1)]M_\odot
\]

The dust temperature is set equal to the colour temperature determined from the \( S_{100}/S_{60} \) flux densities ratio under the assumption that the far-IR emission of early-type galaxies originates from the dust with an emissivity law \( \propto \lambda^{-1} \) at wavelength \( \lambda > 200\mu m \) typical of astronomical silicate. The dust masses calculated using this method are listed in Table 5.2. From Table 5.2 we notice that dust masses derived from colour excess are smaller than those from IRAS flux densities for all the galaxies containing dust. Only for four galaxies we had the needed optical data for the determination of dust mass using total extinction values. For the purpose of comparison, IRAS dust mass for these galaxies are also given in Table 5.3 along with the extinction dust mass and other parameters derived from dust extinction studies. Dust masses as determined from the IRAS flux densities at 60 and 100 \( \mu m \) for NGC 4374 and NGC 1052 are found to be larger, approximately by an order of magnitude, than those obtained from total optical extinction values. This is in agreement with a similar result obtained by Goudfrooij et al. (1994c) for a sample of 10 ellipticals. In order to explain this 'mass discrepancy' the existence of a diffusely distributed component of dust arising from stellar mass loss within the galaxy has been postulated (Goudfrooij & de Jong 1995). For the case of NGC 2076, however, the two estimates are nearly equal, while for NGC 3397 IRAS data is not available for the computation of the dust mass. In a recent paper Bregman et al. (1998) have examined a sample of early-type
Table 5.2: Dust mass from colour index and IRAS data.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Colour excess</th>
<th>$M_d(B-V)$</th>
<th>$M_{d,IRAS}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 0016</td>
<td>0.140</td>
<td>$1.13 \times 10^4$</td>
<td>$&lt; 1.01 \times 10^5$</td>
</tr>
<tr>
<td>NGC 1052</td>
<td>0.105</td>
<td>$1.61 \times 10^4$</td>
<td>$1.69 \times 10^5$</td>
</tr>
<tr>
<td>NGC 1199</td>
<td>0.074</td>
<td>$4.25 \times 10^4$</td>
<td>$&lt; 3.68 \times 10^5$</td>
</tr>
<tr>
<td>NGC 2076</td>
<td>0.156</td>
<td>$1.80 \times 10^6$</td>
<td>$3.67 \times 10^6$</td>
</tr>
<tr>
<td>NGC 2110</td>
<td>0.185</td>
<td>$2.86 \times 10^5$</td>
<td></td>
</tr>
<tr>
<td>NGC 2274</td>
<td>0.102</td>
<td>$1.41 \times 10^6$</td>
<td>$&lt; 2.89 \times 10^6$</td>
</tr>
<tr>
<td>NGC 3497</td>
<td>0.146</td>
<td>$1.29 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td>NGC 4374</td>
<td>0.022</td>
<td>$3.74 \times 10^4$</td>
<td>$1.00 \times 10^5$</td>
</tr>
<tr>
<td>NGC 5813</td>
<td>0.032</td>
<td>$4.46 \times 10^4$</td>
<td>$&lt; 9.45 \times 10^4$</td>
</tr>
<tr>
<td>NGC 6758</td>
<td>0.023</td>
<td>$1.67 \times 10^4$</td>
<td>$6.80 \times 10^5$</td>
</tr>
<tr>
<td>NGC 6776</td>
<td>0.052</td>
<td>$7.60 \times 10^5$</td>
<td>$1.80 \times 10^6$</td>
</tr>
<tr>
<td>NGC 6868</td>
<td>0.134</td>
<td>$9.88 \times 10^3$</td>
<td>$2.35 \times 10^6$</td>
</tr>
<tr>
<td>NGC 6958</td>
<td>0.050</td>
<td>$2.33 \times 10^4$</td>
<td>$1.12 \times 10^6$</td>
</tr>
<tr>
<td>NGC 7562</td>
<td>0.059</td>
<td>$9.00 \times 10^4$</td>
<td>$&lt; 4.31 \times 10^5$</td>
</tr>
</tbody>
</table>

Table 5.3: Dust mass from optical extinction.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$R_v$</th>
<th>$&lt;a&gt;/a_{Gal}$</th>
<th>$M_{d,Av}$ ($M_\odot$)</th>
<th>$T_{d,IRAS}$ K</th>
<th>$M_{d,IRAS}$ ($M_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1052</td>
<td>1.98</td>
<td>0.74</td>
<td>$7.9 \times 10^4$</td>
<td>41</td>
<td>$1.7 \times 10^5$</td>
</tr>
<tr>
<td>NGC 2076</td>
<td>2.70</td>
<td>0.89</td>
<td>$3.2 \times 10^6$</td>
<td>36</td>
<td>$3.7 \times 10^6$</td>
</tr>
<tr>
<td>NGC 3497</td>
<td>1.87</td>
<td>0.52</td>
<td>$7.5 \times 10^6$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NGC 4374</td>
<td>2.18</td>
<td>0.80</td>
<td>$1.2 \times 10^4$</td>
<td>37</td>
<td>$1.0 \times 10^5$</td>
</tr>
</tbody>
</table>
galaxies, excluding active, interacting and peculiar cases, all detected by IRAS with an objective to separate FIR emission by stellar mass loss from that by cold dust. They suggest that following a merger of two spirals to form an elliptical, entire dust would be in merger remnant and it would be detected by both through FIR emission and optical extinction, giving rise to equality of dust masses determined from optical extinction and that from IRAS data. With a passage of time, owing to mass loss from stars in the newly formed elliptical the amount of distributed dust grows, which is detected from its FIR emission but extinction measurements fails to detect this uniformly distributed component. As a result, the ratio of IRAS dust mass to the extinction mass increases with time, and therefore, this ratio for the known merger remnants may be used to determine the time elapsed since the last merger.

Assuming this picture to be correct, it is very tempting to speculate the galaxy NGC 2076 to be a case of recent merger, as dust mass estimates from IRAS flux and that from optical extinction values are nearly equal. This, however, requires more detailed observations on this galaxy for it to be called a recent merger. For other early-type galaxies, containing large scale dust showing FIR emission at 60 and 100 \( \mu \text{m} \), and have other signatures of merger remnants in them, it is required to compare dust masses from FIR emission and total extinction in order to substantiate the arguments advocated by Bregman et al. (1998).

5.3.4 Properties of the stellar disk in NGC 4564

NGC 4564 is an elliptical galaxy subclassified as an E6. Previous investigations (Goudfrooij et al. 1994a; Michard & Marchal 1994) on this galaxy had shown it to have a fairly prominent disk aligned with its apparent major axis. We have carried out detailed isophotal shape analysis of this galaxy, and performed bulge-to-disk decomposition of the brightness profile of the galaxy to derive the best fit characteristics scale lengths for the two components and the disk-to-bulge ratio. Our detailed structural analysis reveals the disk to be highly flattened one as compared to the underlying bulge, a feature which is consistent with the kinematical properties of the galaxy (Sahu et al. 1996a).
Results and discussion

Figure 5.20: R band residual image of NGC 4564 showing stellar disk along major axis.

Image decomposition into bulge and disk

With a view to separate the spheroidal component, a certain fraction (up to 40%) of the brightest pixels are clipped at each stage of ellipse fitting, and a smooth model is generated. The smooth model is subtracted from the original galaxy image to obtain residual image which reveals extra brightness along the major axis of the galaxy (Figure 5.20). This shows the presence of a prominent stellar disk lying along the apparent major axis of the galaxy. The residual image is subtracted from the original galaxy and ellipses are again fitted to this and the procedure is repeated until the disk subtracted galaxy is left with perfectly elliptical isophotes. The profiles of disk free galaxy is used to get the parameters of bulge by fitting de Vaucouleurs law to it. The best fit parameters for bulge are found to be: effective radius of the bulge $r_e = 40.8''$, ellipticity = 0.35. The best fit bulge image constructed with the above parameters using artdata task within IRAF is subtracted from the original galaxy, to obtain the disk component embedded in the galaxy. This can be used to make an initial guess for the disk parameters. In order to examine the properties of the disk, perfectly exponential disks are modeled with central surface brightness
1_0 and scale length r_d. The other parameters i.e. inclination and position angle are kept free. The disk models are then convolved with the seeing psf and added to the spheroidal component to obtain the model galaxy. Isophotal profiles obtained for the model galaxy are compared with those of the original galaxy. The dependence of model galaxy profiles on disk parameters is studied by varying disk parameters. The comparison between the model galaxy profiles with those of original galaxy gives an estimate of the inclination of the disk, position angle and central surface brightness. The profiles of isophotal parameters are plotted in Figure 5.21 for the model and the original galaxy. The best fitting parameters derived for the disk embedded in the galaxy are: scale length of the disk r_d = 28.14", axial ratio b/a = 0.3 and position angle = 40°.

A comparison of the ellipticity for the two components shows that the stellar disk embedded in NGC 4564 is highly flattened as compared to the bulge. Further, the small inclination ~ 18° of disk from the line of sight makes it a suitable galaxy for the detection of the embedded disk. The ratio (v/σ) of velocities corresponding to the rotational kinetic energy and that corresponding to the kinetic energy of line of sight component of random motions is ~ 1.14 (Busarello et al. 1992) for this galaxy, which indicates that this galaxy is rotating fast enough to support a stellar disk. The galaxy is a weak radio source (Heckman 1983) and also is X-ray quiet (Nieto et al. 1994). These properties are consistent with the isophotal properties of the galaxy.

5.4 Conclusions

Some of the important conclusions of the work reported in this chapter are:

1. In this chapter we have searched for the presences of dust, shells and other faint features embedded in early-type galaxies that we observed in the optical as well as in near-IR bands as a part of the thesis work. This has led to detection of new features in several of them. 14 out of the 31 galaxies in our sample are found to have dust either in form of patch or well defined geometries. Nine galaxies were previously known to have dust, while five are the new detections from our analysis. Out of 31 galaxies 9 are found to have other forms of fine structures e.g. shells, X-structures etc, and out of this 7 cases are the new detections. Further, an inspection of the value of b_1, which is usually taken to quantify isophotal distortions from elliptical isophotes, on one hand and presence
Figure 5.21: Profiles of the shape deciding parameters for the original and modelled galaxy.
of dust and other faint features, on the other, there does not seem to be a clear cut one-to-one correspondence between the two.

2. We have investigated the wavelength dependence of the dust extinction using optical broad band surface photometry of four early-type galaxies known to have dust in the form of lane or ring. In all the four cases the extinction curves are found to run parallel to that of the Milky Way, suggesting that the physical properties of the dust are similar to that of our Galaxy. The ratio of total to selective extinction $R_V$ for these galaxies is found to be smaller than the canonical value of 3.1 for our Galaxy. This in turn indicates that the dust grain size responsible for extinction in these galaxies is smaller than that of the Milky Way. Previous studies of dust extinction properties in early-type galaxies gave similar results (Brosch & Loinger 1991, Goudfrooij et al. 1994c).

3. We have estimated the total dust mass in all the galaxies containing dust patch or lane or ring etc. by three different methods: (a) optical colour excess, (b) total extinction value and (c) FIR emission. Dust masses as determined from IRAS fluxes are always found to be larger than those from optical colour excess as well as that from total extinction values, wherever available. Following Bregman et al. (1998) a comparison of IRAS dust mass and extinction dust mass for the known cases of merger remnants, may provide a good indicator of the time elapsed since the last merger.

4. We have also carried out a detailed photometric analysis of galaxy NGC 4564 to find that (a) the galaxy possesses a highly flattened stellar disk along its major axis, in consistent with the kinematical properties of the galaxy, (b) the best fit structural parameters for the bulge and the disk are:

(I) Bulge : $r_e = 40.8''$, ellipticity = 0.35

(II) Disk : $r_d = 28.14''$, ellipticity = 0.70, and

(III) Disk-to-Bulge ratio = 0.18.

Generally, the dust mass estimation using the FIR flux are found to be nearly one order of magnitude higher than that from total optical extinction, except for the case of recent mergers, for which case the two estimates are equal.