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Polarimetric imaging of the polar ring galaxy NGC 660 – evidence for dust outside the stellar disk

P.B. Alton[1], **D.P. Stockdale**[2], **S.M. Scarrott**[2], **and R.D. Wolstencroft**[3]

[1] University of Wales, Department of Physics & Astronomy, P.O. Box 913, Cardiff CF2 3YB, UK
[2] University of Durham, Physics Department, South Road, Durham DH1 3LE, UK
[3] Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ, UK

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Abstract. Optical imaging polarimetry has been carried out for the polar ring, starburst galaxy NGC 660. This galaxy has a highly inclined, severely tidally-disturbed disk which is surrounded by a gas-rich, polar ring. We detect scattered light from a large part of the halo and this is attributable to dust grains residing up to $\simeq 2.5$ kpc from the stellar disk. There is evidence from emission-line imaging carried out in the past, that NGC 660 is host to an energetic outflow of hot gas along the minor axis (a 'superwind'). Our results indicate that dust grains are entrained in this same outflow. Polarization due to scattering, however, is also present at positions away from the minor axis suggesting that grains may also be displaced from the stellar disk by tidal forces exerted during galactic collisions.

Where the polar ring occludes the stellar disk we observe polarization due to magnetically aligned, dichroic grains. By comparing the recorded polarization with the associated optical extinction we infer that the magnetic field in the ring has a lower (but still comparable) strength to the magnetic field in the Milky Way. We also derive a dust-to-gas ratio for the ring and this is about a factor of 2-3 lower than in the solar neighbourhood (but close to the value measured in some nearby spirals). If the ring comprises the remnants of the 'interloper' which collided with NGC 660, we expect that the ruptured galaxy was a massive, metal-rich spiral.

Key words: ISM: dust, extinction – ISM: magnetic fields – galaxies: interactions – galaxies: individual: NGC 660 – galaxies: intergalactic medium – polarization

1. Introduction

NGC 660 is almost unique as a nearby, gas-rich, disk galaxy which is surrounded by a large polar ring. Most galaxies characterized by such unusual morphological structures belong to the elliptical and SO group of galaxies which are notably gas poor (Schweizer et al. 1983). The disk of NGC 660 is viewed close to edge-on ($i = 70°$) and is bisected by a prominent dust lane (Fig. 1). The inclination of the ring varies from about $45°$-$55°$ with respect to the plane of the disk and, in this sense, the ring is not truly 'polar' although referred to as such within the literature. The tilt in the ring means that differential rotation along the structure should cause dissipation of the configuration within $< 10^9$ years (Combes et al. 1992). Adopting a distance of 13 Mpc to NGC 660 (van Driel et al. 1995; H_0=75 kms^{-1}Mpc^{-1}), the diameter of the ring is estimated to be 25 kpc.

The presence of a polar ring, as well as a rather warped stellar disk (Baan et al. 1992), are strongly indicative of a recent, violent past within the system. A massive 'interloper' either merged with, or heavily perturbed, the pre-existing disk (van Driel et al. 1995) and this has, almost certainly, been the prime cause of the starburst activity which NGC 660 is now experiencing (Leech et al. 1994).

Evidence for prolific, recent star formation within NGC 660 is found over a wide range of wavelengths. Images of the galaxy, carried out in the Hα emission line, testify to the presence of young stars over much of the disk (Armus et al. 1990), although observations carried out at more 'transparent' wavelengths, unaffected by dust extinction, indicate that the nuclear region contains the most energetic activity. Indeed, in the radio continuum, emission emanates primarily from a nuclear torus occupying the inner 250 pc of the disk (Condon et al. 1982). The spectral index of these observations is steep (α=+0.6) indicating that chiefly synchrotron radiation has been detected originating from young supernova remnants. Resolution-enhanced $IRAS$ images of NGC 660 manifest a luminous (2×10^{10}L$_\odot$), compact source within the inner 3 kpc of the disk and this has been interpreted as far infrared (FIR) emission from warm dust enclosing a central starburst (Alton et al. 1998).

NGC 660 has been cited as a possible 'superwind' galaxy. The Hα image of Armus et al. (1990) shows a diffuse, filamentary structure extending for several kpc away from the disk. In many other infrared bright galaxies, these extra-planar, emission-line nebulae have been identified as the shock region surrounding hot gas expelled from the nuclear starburst (Heckman et al. 1990). Hα radiation is also detected from the polar ring although, in this case, the emission is attributable to clumps of newly-formed stars. The polar ring is also fairly blue (V-I$\simeq$1; van Driel et al. 1995) confirming that large numbers of young stars have formed out of the gaseous material which accreted to form the structure. Aperture polarimetry, in a V-band filter,

Send offprint requests to: P.B. Alton (paul.alton@astro.cf.ac.uk)

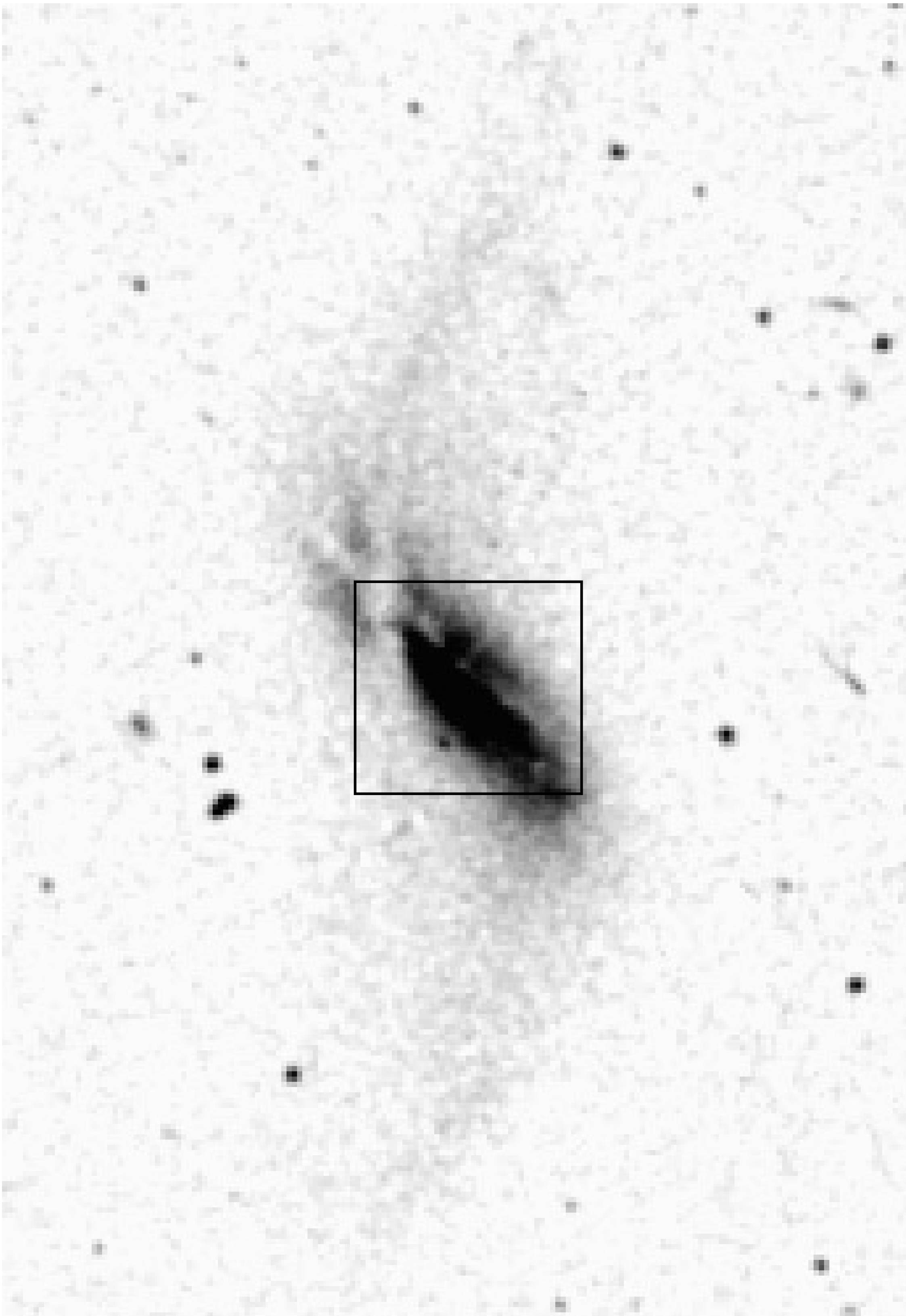

Fig. 1. A negative blue image of NGC 660 taken from the Digitized Sky Survey. North is at the top and east to the left. The size of the image is approximately $6' \times 9'$. A box superimposed onto the disk shows the region displayed in the polarization maps of Fig. 2. The Digitized Sky Survey was produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images on these discs are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and UK Schmidt Telescope.

has been carried out previously for NGC 660 by Reshetnikov & Yakovleva (1991). This investigation consisted of 2 measurements in the main dust lane and 2 measurements along the polar ring (where polarizations of 1.5 ± 0.4% and 6 ± 2%, parallel to the direction of the dust lane and ring, were recorded respectively.)

In this paper, we carry out optical polarimetric *imaging* of NGC 660 and its polar ring. Our investigation forms part of a long-standing project to examine the polarization properties of infrared-bright, starburst galaxies. For many years, the extent of our knowledge was restricted to nearby M82 which exhibits a halo of linearly polarized light extending for a kiloparsec or so 'above' and 'below' the edge-on, stellar disk (Schmidt et al. 1976; Bingham et al. 1976; Chesterman & Pallister 1980). This remarkable phenomenon is caused by dust grains, displaced from the disk, which scatter light from the stellar disk towards the observer (Solinger & Markert 1975). Linear polarization maps of M82, taken in a Hα filter, demonstrate that scattering also makes a significant contribution to the diffuse emission-line radiation recorded in the halo of this galaxy. Dust grains, entrained in the superwind, reflect some of the emission-line radiation which emerges from the central starburst along the minor axis (Scarrott et al. 1991a).

More recently, polarimetric imaging in the optical continuum has been carried out for a small number of more distant starburst galaxies. NGC 1808 is already known, from previous optical and colour imaging (Phillips 1993), to possess spectacular dust filam ents which extend from the central disk up to several kpc into the halo. Scarrott et al. (1993) have detected scattered light over much of the same region indicating that this galaxy, like M82, contains a kpc-scale reflection nebula illuminated by the luminous central starburst. The heavily disturbed, starburst galaxies NGC 2146 and NGC 3256 have also been shown to harbour giant reflection nebulae along their minor axes (Draper et al. 1995; Scarrott et al. 1996). This affect, once again, is almost certainly attributable to dust grains entrained in a starburst-driven outflow.

NGC 660 provides an expedient continuation of the studies described above. Its almost certain involvement in a recent tidal collision (and possible merger) will help determine the respective rôles of galactic interactions and subsequent starburst-driven outflows in redistributing dust and gas around the perturbed system. In Table 1, we provide a summary of the general properties of NGC 660.

Table 1. A summary of the general properties of NGC 660. Using data listed in the RC3 (de Vaucouleurs et al. 1991), we tabulate the size, the morphological type and the blue magnitude corrected for Galactic extinction. The (1950) position is derived from our own astrometric calibration carried out in Sect. 3. The distance is based on the recessional velocity given by van Driel et al. (1995) assuming a value of 75 kms^{-1}Mpc^{-1} for H_0. The far infrared (FIR) luminosity and the FIR-tue luminosity ratio are extracted from Alton et al. (1998) using the distance that has been tabulated. The blue luminosity is derived according to the definition given by Soifer et al. (1987).

Parameter	Value
Right ascension (1950)	01h 40s 21.7
Declination (1950)	$+13^\circ\ 23'\ 37''$
Size ($D_{25} \times d_{25}$)	$8.3' \times 3.2'$
Type	SBa(s) pec
Far infrared Luminosity ($L_\odot$)	2×10^{10}
Magnitude B_T^0	11.4
Distance	13 Mpc
FIR-to-blue luminosity ratio	4.0

2. Observational details

NGC 660 was observed at the f/15 Cassegrain focus of the 1-meter SAAO telescope during November 1993. The Durham imaging CCD polarimeter was used at the base of the telescope in conjunction with a broad V-band filter (550±130nm). The instrument field of view is approximately $11' \times 8'$, although, due to a mask at the entrance of the polarimeter, only half of this area can be imaged at any one time (see below). In all, 12 CCD frames were obtained, each lasting 600 seconds. These exposures ensured adequate signal-to-noise levels over the brightest part of the galaxy (essentially the main disk).

The Durham Optical Polarimeter measures the polarization of astronomical objects by using a superachromatic half-wave plate and a Wollaston prism. The latter splits the incident light into two beams of mutually orthogonal polarization. These are brought to a focus, as left and right images, on adjacent parts of a blue-coated CCD. To prevent overlap on the chip, a mask in the focal plane of the telescope occludes alternate strips of the incident image so that, eventually, the telescope must be moved if all parts of the target are to be observed. The polarization angles of the orthogonal beams are controlled by the retardance device, the half-wave plate, and this is set to various position angles in order to eliminate systematic instrumental effects and determine the polarization of the object. Since the instrument uses a dual-beam, recording orthogonal polarizations simultaneously, it is a straightforward matter to correct for variations in the night-sky transparency during exposures. A more complete description of the instrument optics is found in Scarrott (1991).

The reduction of raw data from the Durham optical polarimeter has been described in detail elsewhere (Draper 1987; Warren-Smith 1979) and therefore we summarize it only briefly here. Object frames from the CCD are flatfielded using flatfields obtained during the same night. Adjacent left and right hand images within the flat-fielded frames are then aligned with each other using foreground stars as fiducial markers. A sky subtraction is made and then the aligned frames are normalized in order to eliminate (minor) differences between the two polarimeter channels and variations in the sky transparency. By comparing the difference in intensity between these normalized images one obtains the level and direction of polarization at each point within the object. An 'in-house' suite of computer programs is used to carry out the reduction procedure described above.

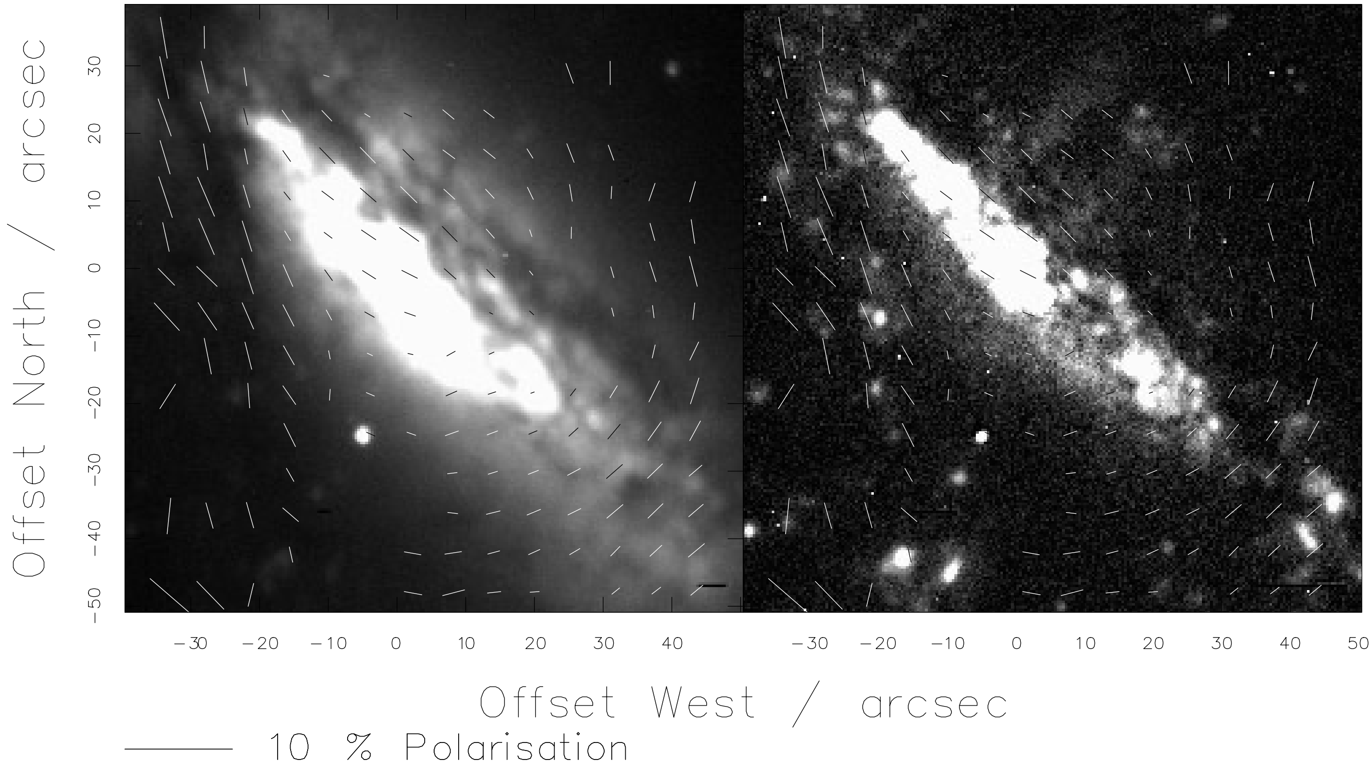

Fig. 2. V-band linear polarization vectors overlayed onto an R-band (left) and Hα (right) image of NGC 660. The axes are labelled as arcminute offsets, north and west, from the nucleus which has an estimated (B1950) position of: 01h 40s 21.7, +13° $23'$ $37''$ (Sect. 3). In both images, the displayed region corresponds to the box in Fig. 1. The polar ring encircling the galaxy runs north-south crossing the disk $30''$ north-east of the nucleus. Note the presence of intense emission-line radiation inside the disk and clumpy HII regions along the polar ring. The diffuse Hα filaments extending north-west of the central disk are believed to be caused by the expansion of hot gas from the nuclear starburst (Armus et al. 1990). Both the R-band and Hα images have already been presented elsewhere (Armus et al. 1990).

A natural by-product of the measurement process is an intensity image of the observed object (in this case a broad V-band image of NGC 660). In addition to this, two images of NGC 660 were kindly made available to us by L. Armus from Palomar Observatory Caltech. One is taken in continuum-free Hα + [NII] emission (hereafter referenced simply as Hα) and the other is an R-band image (broad-band Mould R filter). Both images have already been presented and described elsewhere (Armus et al. 1990). Registration between the polarimetric data and the emission-line/R-band images was possible using fiducial stars.

As with all polarimetric observations of extragalactic objects it is important to consider the polarizing affect of dichroic grains within the Milky Way. NGC 660 is not particulary close to the Galactic plane (l=$141.6°$, b=$-47.3°$) and, therefore, we do not expect it to be significantly affected by grains aligned in the Galactic magnetic field. Indeed, the measurements of Matthewson & Ford (1970) suggest an interstellar polarization of no more than 0.5% in this region. This is generally lower than the noise level within our data.

3. Results

In Fig. 2, we show the V-band polarization measured in NGC 660 superimposed onto the R-band and Hα images. The data are displayed in the conventional manner with vectors proportional to the linear percentage polarization and their direction corresponding to the orientation of the electric field. To acquire sufficient signal-to-noise, the polarization is determined for bins of size $11'' \times 11''$ (0.5 kpc^2). The separation between neighbouring measurements is $6''$ (380 pc). The relatively high sampling gives a smooth appearance to the polarization map but it also means that adjacent vectors are not strictly independent of each other. Errors in the percentage level and direction of polarization are of the order of 0.5-1% and $15°$ respectively (with the uncertainty lowest in the brightest part of the galaxy). Axes are labelled as arcsecond offsets from the galactic nucleus. Our own astrometry, carried out using the HST guide star catalogue and the Palomar Sky Survey, gives the nucleus an estimated (B1950) position, in the V-band, of: 01h 40s 21.7, +13° $23'$ $37''$.

Fig. 2 shows that large parts of NGC 660 are linearly polarized up to the level of 3-4%. Various configurations of the vector pattern are evident and these are now described in turn.

The two dark lanes conspicuous in the R-band image can be identified with: (i) a rather warped dust lane contained *within* the disk and; (ii) the polar ring *crossing* the main disk at $30''$ north-east of the nucleus. In both these regions, the vectors are orientated along the direction of the absorption feature, which is typical of polarized light generated by dichroic extinction. Dichroism is thought to be caused by elongated, paramagnetic grains which are partially aligned with a magnetic field. The alignment means that the grains preferentially absorb and extinguish light with an electic field perpendicular to the magnetic field lines. As a consequence, the light which escapes is imbued with a polarization which is parallel to the direction of the magnetic field (see Purcell 1979; Davis & Greenstein 1951 for a discussion of this affect). Polarization due to dichroism has been recorded in the dust lanes of several nearby galaxies and is seen to follow the spiral configuration of the large-scale magnetic field (e.g. Scarrott et al. 1991b; Scarrott 1996). The polarization levels that we record in the absorption lanes of NGC 660 (1-2% in the main dust lane and 2-4% in the polar ring) are consistent, within the uncertainties, with the corresponding values given by Reshetnikov & Yakovleva (1991)[1.5 ± 0.4% and 6 ± 2% respectively]. The alignment of the polarization angle, at all times, with the absorption lane direction is also noted by these authors.

Significant polarization is also recorded *outside* the disk of NGC 660 and this is unlikely to be a result of preferential absorption of background light by aligned grains. The two main regions concerned are: (i) along the diffuse Hα filaments extending north-west of the central disk (this is the putative shock region of the starburst-driven outflow identified by Armus et al. 1990); (ii) the centro-symmetric pattern 'above' and 'below' the south-west part of the disk. The polarization observed in these areas is almost certainly attributable to scattering from dust outside the disk. The reflection of optical light by classical dust grains (size$\sim 0.1\mu$m) induces a polarization perpendicular to the scattering plane – a phenomenon well established in Galactic reflection nebulae (Scarrott 1988; Scarrott 1991). This creates a centro-symmetric vector pattern in the plane of the sky so that, if the vectors were rotated by $90°$, they would then point directly to the light source(s) illuminating the dust. This scenario clearly fits the case for the aforementioned regions. Thus, the centro-symmetric polarization detected 'above' and 'below' the south-west part of the disk indicates that grains, present in these regions, are reflecting starlight originating from the south-west disk towards the observer. Similarly, the polarization of the outflow region is attributable to radiation from the inner disk and central starburst emerging along the minor axis but then subsequently scattering of f dust grains present in the outflow.

4. Discussion

4.1. 'Displaced' dust grains

The scattered light that we have detected outside the disk of NGC 660 is very reminiscient of the kpc-scale reflection nebulae already identified in the starburst galaxies M82, NGC 1808 etc. (Sect. 1). In common with these galaxies, we measure significant polarization in the superwind region, suggesting that dust grains are also being lost from the disk of NGC 660, entrained in the outflow. For all these galaxies, the associated level of polarization is similar ($\sim$ 2%) although, within the outflow of M82, values more akin to Galactic reflection nebulae are recorded ($\sim 20 - 30$%). This difference may be an inclination effect. M82 is viewed edge-on, therefore scattered (polarized) light emanating from the halo is less likely to be diluted by unpolarized disk light. Admittedly, however, the inclination of NGC 660 is estimated to be rather small ($20°$; van Driel et al. 1995) suggesting that other factors apart from inclination angle may play a rôle. One possibility is that a large number of stars have been deposited in the halo of NGC 660 during the merger process (Schweizer et al. 1983). This would also tend to diminish the polarization recorded outside the disk.

An interesting issue is *how* the grains that we have detected are being transported by the superwind. Optical and near infrared colour maps of M82 indicate greatest extinction at the limb of the outflow region (Ichikawa et al. 1994,1995). This strongly suggests that the dust is entrained at the boundary of the superwind and, effectively, 'dredged up' from ambient material in the disk. (The 'vertical' filaments evident in colour images of NGC 1808 also argue for containment within a higher density, optically thick medium). In contradistinction, we might expect that any grains produced in the starburst and carried out within the superwind plasma itself, exist as diffuse, tenuous dust clouds extending throughout the entire volume of the outflow cavity. Curiously, the scattered light along the minor axis of M82 and NGC 660 is detected over a large part of the outflow region (in NGC 660 this is delineated by the diffuse Hα extending north-west of the nucleus), suggesting that, in this case, we are perhaps tracing the more tenuous grain component rather than narrow optically thick filaments. A clarification of how dust is distributed within starburst-driven outflows, along with how the extinction and polarization features are related, should be possible by mapping emission from the grains themselves. The latest generation of sensitive submm/mm arrays (SCUBA on the JCMT and IRAM; Sundell et al. 1996; Guelin et al. 1993), with their $\sim 10''$ resolution, are suitably designed to carry out this task in the near future (Alton et al 1999).

In addition to the outflow region, large parts of the NGC 660 halo are also polarized due to scattering from dust grains. In fact, judging from the Hα image displayed in Fig. 2, dust extends up to a projected distance of $40''$ (2.5 kpc) from the disk. We suggest that these grains arrived at their present location either through the circulation of material in the halo by the superwind (a galactic fountain effect; Corbelli & Salpeter 1988) or as a result of tidal forces exerted during the galactic collision. There is strong evidence that close gravitational interactions can lead to the displacement of gas (and probably, therefore, dust) from its more conventional interstellar environment. For example, Yun et al. (1994) recently used the VLA to map out 21cm emission in the nearby M81 group. Their results show that a network of high column density, intracluster HI 'bridges' connect the various members of this closely gravitationally-bound group of galaxies. In a similar vein, Hughes et al. (1991) purport to have detected a FIR (and therefore dust) counterpart to the tidally-generated optical/HI plume in the Leo triplet of galaxies. Even within the NGC 660 system itself, the presence of dust in the polar ring (see below) confirms that dust can exist in environments outside the conventional stellar disk. Clearly, the difficulties in detecting dust outside the galactic disk can be quite considerable. The grains are likely to be cold, and therefore difficult to detect in emission. Unlike the dust lanes in spiral disks they are also probably inconspicuous as absorption features. In this context, imaging polarimetry offers a novel means of tracing dust grains outside the disk by capitalizing on their tendency to scatter (and therefore polarize) starlight.

Whilst our data allow us to make general inferences about the distribution of dust outside the disk of NGC 660, it is far less easy to estimate the *mass* associated with this grain material. Calculations of this kind have been carried out in the past (making certain assumptions about scattering geometry and grain size etc.) but the overwhelming simplification on these occasions was the visibility of the stellar sources which illuminate the dust grains (Alton et al. 1994; Alton 1996). The situation for NGC 660 is far more intractable since the edge-on orientation of the disk, compounded with the presence of prominent interstellar absorption lanes, contrive to make the underlying stellar luminosity highly uncertain. Even for less inclined starburst galaxies, such as NGC 1808, the calculation would still be problematic since only crude esimates can be made of the intensity of the radiation field impinging on grains along the minor axis. For two cases in the past, where scattering models have been useful (both of them for disk-less, low mass starburst galaxies; Alton 1996), the derived dust mass has been at least an order of magnitude greater than the amount of FIR-emitting dust inferred from $IRAS$ data. The implication, on both these occasions, was that $IRAS$ has a tendency to 'overlook' cold grains, which, due to their extended distribution, may nevertheless be traced using optical polarimetry.

4.2. The polar ring

The polar ring characterizing NGC 660 is of great astrophysical interest not least because NGC 660 may be the only known case of a gas-rich, disk galaxy that possesses such an unusual morphological feature (van Driel et al. 1995). To form a structure of this kind it is probable that the galactic collision which preceded the present starburst activity was an on-axis encounter (Schweizer et al. 1983). Such a violent collision is likely to have severely ruptured the interloping galaxy and, indeed, the material comprising the present-day ring probably represents a large fraction of the collisional remnants. The ring has been found to contain copious amounts of atomic and molecular gas ($4 \times 10^9 \mathrm{M}_\odot$ and $10^9 \mathrm{M}_\odot$ respectively; van Driel et al. 1995; Combes et al. 1992). In other words, the total amount of gas is comparable to that residing in the disk itself. It is evident from the Hα image in Fig. 2, that large numbers of new stars have also formed out of the gas present in the ring (the more extensive Hα image of van Driel et al. indicates that star formation is, in fact, taking place along the whole length of the polar ring). We emphasize that the ring in NGC 660 is also *dust* rich – it partially obscures the stellar disk $30''$ east of the nucleus and, as discussed earlier (Sect. 3), it is polarized by magnetically-aligned dichroic grains.

Two issues which we can begin to address with our observations are both the magnetic field strength and the dust-to-gas ratio within the polar ring. To this end, we note that dichroism within our own Galaxy is described by the following empirical relation:

$$\frac{P_V}{E_{B-V}} \leq 9.0 \;\% \; \mathrm{mag}^{-1} \qquad (1)$$

where P_V is the V-band percentage polarization and E_{B-V} is the corresponding selective extinction (Whittet 1992; Serkowski et al. 1975). In essence, the above relationship quantifies the polarization induced in light which is transmitted through a screen of partially aligned dust grains in a magnetic field. The transmitted beam will suffer an extinction given by E_{B-V} whilst, at the same time, preferential absorption by the aligned grains induces a polarization P_V in the light that escapes. The equality in relation 1 holds for maximum polarizing efficiency, effective when the magnetic field is perpendicular to the observer's line-of-sight. Using the average extinction curve for the Galactic interstellar medium (Whittet 1992; Gordon et al. 1997), E_{B-V} can be expressed as $A_V/3$ and relation 1 becomes:

$$P_V \leq 3.0 A_V \;\% \qquad (2)$$

where A_V is the visual extinction. This can now be directly compared with the polarization recorded in the polar ring of NGC 660. By using relation 2, however, we assume implicitly that the composition and size distribution of classical grains in NGC 660 (size$\sim 0.1\mu$m) are similar to those in the Milky Way (this uniformity certainly appears to be true for galaxies within the Local Group; Fitzpatrick 1989; Bouchet et al. 1985). We obtain the extinction of the ring by effectively 'folding' the galaxy about the minor axis so that, where the polar ring crosses the disk, it is overlayed by a (relatively) unobscured region from the diametrically-opposite (west) part of the disk. The average V-band extinction derived in this way is 1.2±0.1 mag and this corresponds to a mean V-band polarization, in Fig. 2, of 2.7±0.4%. For a circular geometry, the magnetic field in the polar ring will be perpendicular to the line-of-sight where it obscures the disk. Therefore, we derive P_V(%)=(2.3±0.4) A_V which is not far from the upper limit in relation 2. Admittedly, we have neglected the intrinsic luminosity of the ring when calculating the extinction but this is fairly small compared to our quoted error. The dichroic behaviour that we observe in the ring is determined by the properties of the grains (composition, shape etc.) but also by the strength of magnetic field which aligns them (Purcell 1979). If the classical grains in NGC 660 are of a similar nature to those in the Galaxy, we conclude that the magnetic field in the polar ring is slightly weaker than the magnetic field in the Milky Way.

Our detection of dichroic extinction in the polar ring has interesting implications for theories of magnetic field formation in galaxies. It is commonly believed that the large-scale fields found in spiral galaxies are a consequence of a dynamo action caused by the disk rotating over timescales of 10^9 years (Lesch et al. 1988; Kronberg 1994). A more likely scenario for the polar ring seems to be that the magnetic field was originally formed in the galaxy which collided with NGC 660 but that it then remained intact during the tidal disruption. This is consistent with the hypothesis, discussed below, that the present-day system is the merger product of two spiral galaxies.

We can estimate the dust-to-gas ratio within the ring if the value of A_V=1.2 mag, derived above, is typical of the whole structure. Van Driel et al. (1995), who have measured the *gas* content directly, estimate a total mass of $5 \times 10^9 \mathrm{M}_\odot$ in atomic and molecular hydrogen. Thus, using the correlation found by Bohlin et al. (1978), which connects Galactic reddening with gas column density and, taking the width and diameter of the ring as $20''$ (0.95 kpc) and $8.8'$ (25 kpc) respectively (Fig. 1), we derive a dust-to-gas ratio which is a factor of 2-3 lower than the solar neighbourhood ($\frac{1}{500}$ as opposed to $\frac{1}{150} \rightarrow \frac{1}{300}$ for the Galaxy; Whittet 1992; Spitzer 1978). This strongly suggests that the polar ring is fairly metal rich, with a heavy element abundance comparable to spiral disks (Issa et al. 1990). The technique of comparing reddening in surface photometry with the amount of gas known to reside in a bisecting polar ring has previously been applied by Reshetnikov et al (1994). These authors establish dust-to-gas ratios close to the solar value for 3 prominent ring systems using this method (UGC 7576, UGC 9796 and NGC 4650A). In addition, optical spectrophotometry of 11 HII regions in the polar ring of NGC 2685 (the Helix galaxy) indicates a level of oxygen consistent with solar metallicity (Eskridge & Pogge 1997).

If the contents of the polar ring were formerly part of the galaxy which collided with the disk of NGC 660, then our data indicate that the interloper was a massive galaxy with a gas-rich, dusty interstellar medium. The strongly disturbed appearance of NGC 660 reinforces the idea that the present-day system results from the merger of two galaxies which were of comparable mass. Such a chaotic system is unlikely to emerge from ingestion of a small companion (Huang & Carlberg 1997). We have used survey plates to check the environment of NGC 660 but find no convincing evidence for a nearby tidal companion. Indeed, only two galaxies could have conceivably interacted with NGC 660 in the last $\sim 10^8$ years (assuming a velocity dispersion of a few hundred kms^{-1}). UGC 01200, $30'$ to the south, and UGC 01195, $22'$ to the north-east, both have a similar redshifts to NGC 660 (Willick et al. 1990) but neither of them appear massive enough to have caused the disruption we see in NGC 660 today. We feel that a complete merger with a metal-rich, massive spiral is the most likely explanation for the present condition of the NGC 660 system (see also Reshetnikov et al 1994; Eskridge & Pogge 1997).

The extinction that we have measured in the polar ring of NGC 660 may answer another enigma associated with this unusual galaxy. Van Driel et al. (1995) have used their V-I colour measurements to infer an age of a few gigayears for the stars that have formed out of the gas in the ring. The tilt of the ring, however, is generally believed to make the structure unstable over timescales of $< 10^9$years – a paradoxical situation which has been described as “puzzling” by van Driel et al. If we assume a ‘sandwich’ model in which the stellar population suffers half the visual extinction that we have measured for the ring where it crosses the disk, the dereddened colour becomes V-I=0.7 (under the assumption of a Galactic extinction law). This is somewhat lower than the uncorrected colour given by van Driel of V-I=1. The dereddened colour is consistent with an age of $\sim 10^8$ years if the stars in the ring were formed in a short burst (Leitherer & Heckman 1995) and this is no longer incompatible with the stability lifetime.

5. Conclusions

Optical imaging polarimetry has been carried out for the highly-inclined, starburst galaxy NGC 660. Large parts of the halo are polarized in what amounts to huge reflection nebulae extending at least 2.5 kpc from the stellar disk. The grains responsible for this effect scatter starlight from the disk towards the observer and in doing so induce a polarization in the reflected radiation. There is evidence, from emission-line imaging carried out by Armus et al. (1990), that NGC 660 possesses a starburst-driven superwind and the scattering we have detected along the minor axis indicates that dust grains are entrained in the outflow. The situation is very reminiscient of several other superwind galaxies, including the archetypal starburst M82, which are known from both colour imaging and polarimetric observations to harbour dusty outflows. For NGC 660, scattering is not restricted to the minor axis. Indeed, reflection nebulae detected ‘above’ and ‘below’ the south-west part of the disk imply that dust may have also reached its present location either through the circulation of grains via the superwind (galactic fountain effect) or through the influence of tidal forces. The latter is possible because NGC 660 has recently experienced a galactic collision, indeed, probably a merger.

NGC 660 is distinguished by a large ring of gas and stars (many of them newly formed) encircling the main disk. We detect polarization from the ring where it crosses the disk and this is believed to be the result of dichroic extinction by grains aligned in a magnetic field. The polarizing effect is similar to that observed in the Galactic magnetic field, suggesting that the field strength in the ring is fairly high. We also derive a dust-to-gas ratio for the ring by estimating the obscuration of the disk and incorporating previous measurements of gas content (van Driel et al. 1995). The value is about a factor 2-3 lower than the solar neighbourhood but still close to the ratio measured for some nearby spirals (Issa et al. 1990). Since the ring comprises the remnants of the galaxy which collided with NGC 660, we expect that the ruptured galaxy was a massive, metal-rich spiral.

We recommend a closer study of the neutral gas within the NGC 660 system along with its various kinematic components. This might reveal whether the grains situated outside the disk (which we have detected in scattered light) are coupled to the movement of gas round the system. In particular, it would be of interest to learn whether grains ‘above’ and ‘below’ the south-west part of the disk have reached their present location as a result of tidal forces or via dispersion by the galactic superwind. In addition, long-slit spectroscopy is also required in order to firmly establish the presence of a superwind along the minor axis. On a more general note, we believe that this study underlines the need for polarimetric observations of galaxies in various stages of gravitational interaction and subsequent enhanced star formation. This will help to define the respective rôles of tidal forces and starburst-driven winds in displacing dust from its more usual stellar-disk environment.

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