Dust and Extended Ionized Gas in NGC 5044 and its Fellow Radio Elliptical Galaxies

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Introduction

A remarkable discovery of recent years is the detection of cool interstellar matter in a surprisingly large number of apparently "normal" elliptical galaxies. In particular, the technique of co-adding IRAS survey scans has led to the detection of more than half of all ellipticals brighter than $B_T^0 = 11$ mag. in the *Revised Shapley-Ames Catalog of Bright Galaxies* [1] (hereafter referred to as RSA). The far-infrared radiation is most likely explained by thermal emission of heated interstellar dust [2]. In addition, CCD multi-colour surface photometry effectively shows dust patches in some 30% of the cases studied to date [3]. Thorough study of the gas and dust in elliptical galaxies is important to: (1) determine its origin (mass-loss from late-type stars, merging collisions with other galaxies or accretion inflows from cooling X-ray gas), and (2) investigate the three-dimensional shape of elliptical galaxies (oblate, prolate or triaxial) as can be derived from the orientation of the dust lanes and the two-dimensional velocity field of the gas.

Extended ionized gas has been detected in a number of elliptical galaxies. Kinematical studies have shown [4, 5] that the kinematical major axes of gas and stars generally do not coincide. This strongly suggests that the gaseous material has an origin external to the galaxy itself, i.e. brought in during an interaction or merging collision with another galaxy. Moreover, a number of dominant cluster ellipticals containing hot, X-ray emitting gas have been found to contain irregularly distributed dust patches and associated ionized gas in their central regions [6, 7]. Also in these cases, the interstellar matter evidently has an external origin. However, the presence of dust is surprising, since the life time of dust grains exposed to erosion by "sputtering" in hot gas is only of order $10^6 - 10^7$ yrs. To resolve this dilemma, it has been suggested in some recent studies that the dust is replenished by evaporation of cool gas clouds brought in by a recent merging collision [8, 9]. Transfer of heat through electron conduction from the hot X-ray gas to the cooler gas can provide both the excitation for the emission-line gas and the heating of the dust responsible for the far-infrared emission.

To study the global occurrence and properties of dust and gas in elliptical galaxies, we (P. Goudfrooij and T. de Jong from the University of Amsterdam, H. E. Jørgensen and L. Hansen from the Copenhagen University Observatory

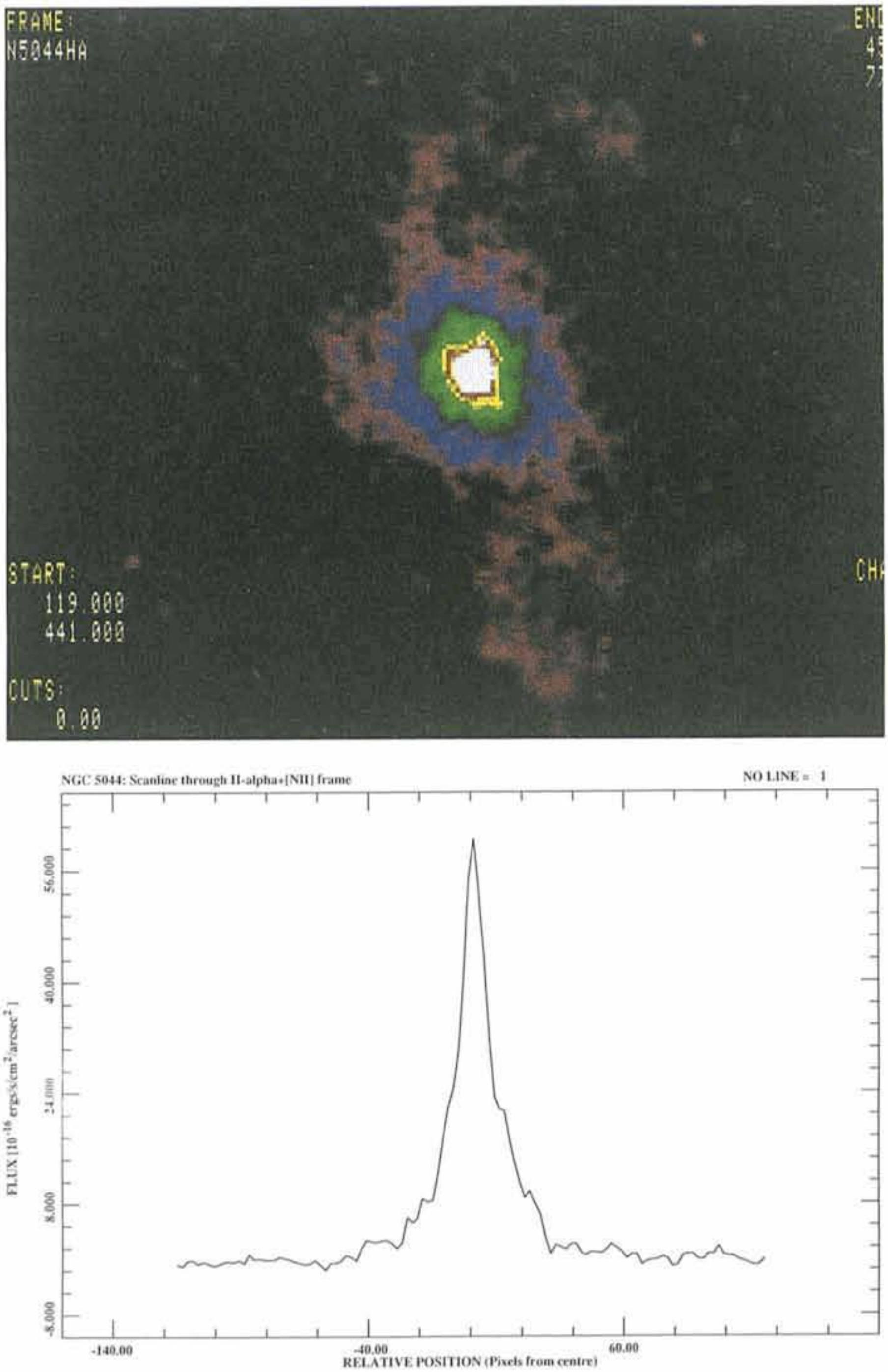

Figure 1(a): *False-colour plot of the Hα+[NII] emission-line flux in the central 1.'31 × 1.'31 of NGC 5044. North is up and east is to the left. Spiral-like features are present at a low level. The frame has been smoothed by a rectangular box of 3 × 3 pixels. This causes the "boxy" appearance of the central region.* (b): *Scanline running through the centre of NGC 5044, in the same orientation as in Figure 2b.*

and H. U. Nørgaard-Nielsen from the Danish Space Research Institute) are currently undertaking an optical survey of a complete, *apparent*-magnitude selected sample of elliptical galaxies, containing all such objects (58 in number) with $B_T^0 < 12$ mag in the RSA catalog. We have performed deep CCD imaging with B, V, and I broad-band filters to study dust patches, and with narrow-band filters centred on the Hα+[NII] emission lines to derive the amount and distribution of ionized gas. The project also involves long-slit spectroscopy at two resolutions. Low-resolution spectra (covering the whole optical region) are used to study the properties of the underlying stellar populations. Template (stellar) spectra will be made using measurements of metallic absorption lines in these spectra. Subtraction of an appropriate template from the spectrum of each object in which the presence of ionized gas has been established by our CCD imaging will reveal the pure emission-line spectrum which can be used to investigate the ionization mechanism of the gas [10]. High-resolution spectra in the wavelength region around Hα are used to determine the kinematics of the gas. Comparison with the stellar kinematics provides information about the origin of the gas. For the southern sample objects, the bulk of the imaging data have already been obtained with the Danish 1.54-m, while the spectra are being taken with the Boller & Chivens spectrographs attached to the 1.52-m and 2.2-m telescopes on La Silla.

Careful Reduction Essential

Since the amounts of dust and ionized gas in ellipticals are very small (generally of order 10^4-10^6 $M_\odot$) compared to the total mass of the galaxy (in most cases one cannot distinguish any sign of it on the "raw" CCD frames), the image processing has to be done carefully. To produce satisfactory B-V, B-I and Hα+[NII] emission-line frames it is essential that the point-spread function is of uniform width and shape in each frame before one can be subtracted from the other. If, for example, the seeing in the I frame is better than in the B frame, then a B-I frame will contain an artificially "red" nucleus, since the I profile contains proportionally more intensity in the central few pixels of the galaxy. An additional problem in producing colour-index frames is the subtraction of the sky background. The "normal size" CCD frames of 320 × 512 pixels are not large enough to include an empty region of sky background when observing these giant elliptical galaxies, and an error as small as 1% in the background subtraction can already lead to unusual elliptical ring-like features with anomalous colours in the colour-index frame. We have therefore made separate sky frames in each (broad-band) filter just before and after each object frame. After elimination of the stellar images in the sky frames we have subtracted these from the object frames. The result is generally very good.

Some Striking Examples: Radio Ellipticals

During the time-consuming routine reduction process, it is quite stimulating when one of the galaxies turns out to be more peculiar than the others. A recently published example of such a galaxy is IC 1459, which exhibits a striking spiral-like disk of ionized gas accompanied by

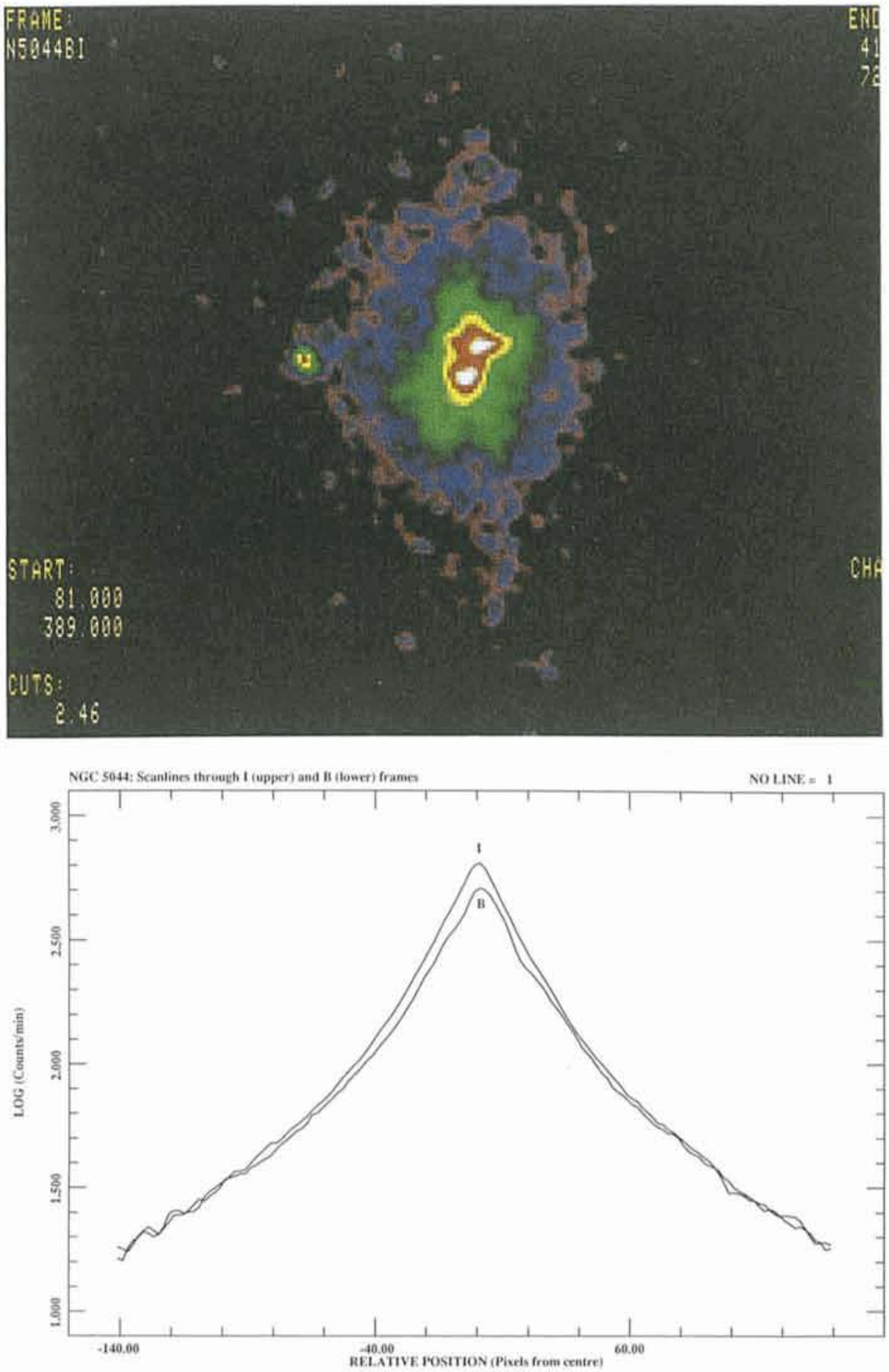

Figure 2(a): *False-colour plot of the B–I colour index in the central 1.′31 × 1.′31 of NGC 5044. Orientation and colour lookup table as in Figure 1a. The two "blobs" near the nucleus are reminiscent of an almost face-on dust ring. The faint spiral-like features (see Fig. 1a) can just be recognized. The source to the east of NGC 5044 is probably a foreground star.* (b): *Scanlines running through the centre and the two dusty "blobs" in the centre of NGC 5044, both for the I and B frames. It can be seen that the B light profile shows "dips" at the positions of the blobs, whereas the I profile is much smoother. The I profile has been shifted to agree with the B profile in the outer parts of the galaxy.*

dust patches [11]. Other interesting features of IC 1459 are: (1) it is a compact, powerful radio source with a flat radio spectrum (the latter feature is an indication of "activity", since most quasars also show it; we hereafter refer to this feature as CNFRS [from Compact Nuclear Flat-spectrum Radio Source]), and (2) it contains a (stellar) core which is kinematically decoupled from the outer body of the galaxy (a "counter-rotating core") [12].

Here we want to point out that these features may be quite common to ellipticals with a CNFRS. All of the southern ($\delta < 0°$) ellipticals in our sample which are listed in the literature as having a CNFRS [13] are found to exhibit extended Hα+[NII] emission, most of the time associated with dust patches.

As another striking example of the class of peculiar ellipticals with a CNFRS we present here results of our observations of the E0 galaxy NGC 5044. This giant elliptical (B_T=11.92, M_B=−21.61) is a member of a small group at a distance of 56 Mpc (H_o = 50 km $s^{-1}Mpc^{-1}$), containing 3 galaxies. Hot X-ray gas has not been detected, but the presence of dust is indicated by a (marginal) detection of NGC 5044 by the IRAS satellite at 60 and 100 μm. Figure 1a shows the distribution of the ionized gas. This frame has been produced using background-corrected exposures by subtraction of a scaled frame containing purely stellar continuum light from a frame containing both stellar continuum and Hα+[NII] emission. Just like in the case of IC 1459, spiral-like structure can be seen at a low level. These features are probably tidal tails which reflect the response of the gas in the gravitational potential of NGC5044 after the capture of a gas-rich galaxy. The emission is dominated by the nuclear region, as can be seen in Figure 1b. Associated with the ionized gas, dust patches are revealed by the B-I colour frame (Fig. 2a). The spiral-like extensions to the north and south can just be recognized. In addition, two "blobs" of high reddening are present near the centre. In Figure 2b we show a scan line running through these two "blobs" in both the B and I frames. It can be seen that the blobs correspond to a local deficit of light in the B frame relative to that in the I frame, and the reddening is therefore assumed to be caused by absorbing dust. A possible interpretation of the two blobs is that we are observing a small nuclear dust ring seen almost edge-on, but to be more convinced of this we must await kinematical data on NGC 5044, which will be obtained during ESO observing Period 47.

We emphasize that, in addition to IC1459 and NGC5044, other ellipticals with CNFRS have been shown to have extended ionized gas which is generally kinematically decoupled from the stellar velocity field, e.g. NGC5077 [5], NGC6868 [14], NGC1052 and NGC6958 [15]. This strongly suggests that this phenomenon is linked to the presence of a CNFRS. In addition to this we note that a number of dust-lane ellipticals show extended radio emission, usually in the form of twin antiparallel "jets". In these cases it has been shown [7, 16] that the radio jets are aligned perpendicularly to the dust lane. A possible interpretation of this is discussed below.

Building Ellipticals by Mergers

Summarizing the case of elliptical galaxies with a CNFRS, we note that all (at least in our sample) exhibit extended ionized gas, and in all cases but one (NGC 1399), dust is seen associated with the ionized gas. Apart from that, we remind the reader that an elliptical galaxy is recognized by the characteristic way in which its surface brightness falls off with distance from the centre, generally called the de Vaucouleurs or $R^{1/4}$ law. At this point we would like to draw a parallel between ellipticals and the so-called "Luminous Far-Infrared Galaxies" (hereafter LFIRGs), which are evidently involved in mergers [17]. In optical images, LFIRGs are irregular (and often multiple) systems, dominated by chaotic patterns of dust. It has recently been reported that several *LFIRGs also follow the $R^{1/4}$ law when imaged in the near infrared,* where the light is largely radiated by old stars which were formed well before the merger [18]. Apparently, the old stars in these galaxies have already settled into a distribution typical of an elliptical galaxy. The nuclei of LFIRGs generally exhibit optical emission-line spectra which are reminiscent of active Seyfert nuclei, heavily reddened by dust which is also responsible for the high far-infrared luminosities of these galaxies.

There is much observational evidence that nuclear activity can be triggered by a merging event. From a theoretical point of view, the mechanisms that could transport gas and dust involved in the merger from about one hundred parsecs (which is the scale of a typical nucleus) down to scales ten orders of magnitude smaller where the gas can feed the active "monster" [19] are poorly understood. The main question is how the gas can lose its angular momentum during infall. However, it has recently been shown that interactions and mergers can be quite effective in redistributing angular momentum in galaxies. Numerical simulations of interacting galaxies *containing gas and dark matter* show that the interactions can generate strong gravitational torques that remove angular momentum from the gas so that it can sink to the centre (e.g., [20]). If an active nucleus is formed, it may destroy the surrounding dust and subsequently reveal a nuclear "monster" of non-thermal radio emission. We emphasize that these features are just what is observed in ellipticals with CNFRS like IC 1459 and NGC 5044.

In view of the evidence mentioned above, we may attempt to draw the parallel between LFIRGs and radio ellipticals somewhat further. The near-infrared imaging results of LFIRGs support the idea that some ellipticals are forming in the present epoch as a result of mergers. Indeed, the radio ellipticals could well be analogues to LFIRGs, but in a more advanced stage of evolution after the merging collision. In this view, the radio ellipticals have either almost blasted away the dust surrounding the monster or the dust and gas have meanwhile settled in one of the possible preferred planes in the galactic potential, whereby the radio jets could develop perpendicular to this plane. In analogy, the active radio source in an elliptical with CNFRS may be expected to develop jets. High-resolution radio observations of the southern ellipticals with CNFRS using the new Australian Telescope array would therefore be quite valuable.

As to the ionization of the extended ionized gas in e.g. NGC 5044, this is most probably due to shock heating in cloud-cloud collisions which are expected during the process of gas infall. In this respect we note that a 60 Å/mm spectrum of NGC 5044 in the wavelength region around Hα [21] shows emission-line intensity ratios [NII]/Hα and [SII]/Hα typical for the class of Low-Ionization Nuclear Emission-line Regions (LINERs) [22], which are well fitted by models of shock waves moving at ~ 100 km s^{-1} through a medium with densities of 10–100 atoms cm^{-3}. We will study the behaviour of the doublet ratio of the [SII] lines (which is a measure of the density of the ionized gas) along the slit of a high-resolution spectrum to check if there is a density gradient in the gas. We note that all bright galaxies in the sample of Heckman [22] containing a LINER *and* a CFNRS are early-type galaxies.

Our extensive dataset of elliptical galaxies may soon tell us what fraction shows lurking active nuclei; the spectroscopic data will help relating the observed characteristics of gas and stars to the merger picture.

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Spiral Galaxies on the Chess Board

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1. Introduction

Last summer I published a Letter in the scientific journal *Nature* in which evidence was presented for a relatively high content of obscuring dust in spiral galaxies. This work, together with a more detailed analysis of the properties of the light absorbing bodies (ESO preprint 730) and a study of the rotation curves of some dusty spiral galaxies with González-Serrano (ESO preprint 731) was high-lighted in an ESO press release (PR 07/90 No "Missing Mass" in Opaque Spiral Galaxies?). Here, I will address some comments and frequently asked questions related to this work.

The new analysis of the dust content of spiral galaxies is based on data from *The Surface Photometry Catalogue of the ESO-Uppsala Galaxies* (by Lauberts and myself, in short ESO-LV), a project which was described in the *Messenger* (LV 1983, 1989). In the Introduction to this catalogue, which contains about 180 parameters for 16,000 galaxies, an extensive discussion is given of the photometric accuracy (thought to be better than 0.15^m in surface brightness) and the completeness and selection effects of this galaxy sample and its various subsamples. Today, after two years of intense research on this data base, it is a great pleasure to say that only a very minor amount of errors have been found so far and I would like to use this opportunity to express my deep appreciation for the enormous dedication of my co-author Dr. Andris Lauberts, who worked full-time on this project for so many years.

The basic idea to study the dust content and hence the degree of transparency in spiral galaxies by means of photometric data is very simple. We think of spirals as flattened round disks that contain dust and stars. Stars emit light; dust particles absorb and scatter light (together called "extinction"). When such a disk is seen from the top it appears round and we see the integrated star light attenuated by the dust along the line of sight. When we see the same disk at a tilted viewing angle, the line of sight will have a larger path-length through the disk, hence it will meet more stars, but also more dust. The tilt angle of the intrinsically round disk can be deduced from its observed axial ratio a/b.

The basic steps to study the transparency are then: (i) to select a *sample* of spiral disks with supposedly similar intrinsic properties, (ii) to make *models* of the spatial distribution of both the dust and the stars in a disk, (iii) to make an analytical solution for these models, describing how for a certain dust content, various *photometric parameters* are expected to change with viewing angle or *a/b* and, eventually, (iv) to fit these models to the photometric parameters of the sample galaxies.

Although, in theory, these steps appear rather simple and straightforward, in practice the choice of samples and its effect on the other steps is quite delicate. The discussion in the literature is extensive and complicated, not only by the different photometric parameters used for the analysis, but also by the wildly different properties of the different sub-samples used. Table 1 summarizes a few of the most popular photometric parameters used (horizontal direction) while, vertically, different employed sub-samples are listed. Basically, each of the 64 boxes in the table can provide information on the effective transparency, but for each box one has to evaluate the *intrinsic distribution* of the particular parameter used and its relation to the observed distribution, both as a result of *selection effects* and effects of incompleteness. The selection effects are so much dependent on both the type of parameters used and on the selection criterion employed, that each box constitutes its own story. Most selection effects are distance dependent and the degree of complication is further quadrupled when the particular parameter used for the test is in itself distance dependent. In Table 1 distance dependent parameters and sample cuts have been shaded, high-lighting the 'doubly difficult' boxes.

Related to the distance dependent selection effects is the so-called Malmquist bias, an effect that puts categories of objects into a sample even while their average intrinsic parameter value would have prohibited them to pass the selection criterion. This is because of the dispersion around that average value, either due to a cosmic dispersion or due to measurement errors. Since there exist more faint than bright galaxies, the Malmquist bias has some amplification and lets more faint galaxies enter a sample than bright ones drop out. A similar effect is well known in radio astronomy, when counting radio sources close to the noise level of the observations.

To complicate matters even further, one has to care about the possible presence of spheroidal bulges that off-set the assumption of disky objects. Fortunately, the effect of bulges can be shown to be very minor for Spirals of type ≥3 (Sb, Sc, Sd). This has also