THE DUSTY DISK OF THE EARLY GALAXY NGC 3656

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Abstract
SHARC II 350 μm continuum and archival HST J−H band maps are presented of NGC 3656, the brightest of our sample of six elliptical galaxies for which resolved CO gas disks have recently been detected with 7′′-spatial-resolution, interferometry mapping. These gas disks confirm the conclusions of earlier results showing optical dust lanes and unresolved CO that implied the common existence of molecular gas in ellipticals and the disk-like structure of this gas. The presented SHARCII mapping results provide the best to date resolved FIR-submm extent of NGC 3656 and of any elliptical galaxy > 40 Mpc, showing that dust of 29 K exists out to at least ∼1.8 kpc in this galaxy. These new data are used in conjunction with the archival HST maps and other published data to determine dust properties and associations with galactic structures, including dominant heating sources such as star-formation or diffuse-stellar radiation.

Keywords: galaxies: elliptical and lenticular, cD — galaxies: individual (NGC 3656) — galaxies: ISM — galaxies: structure — infrared: galaxies — submillimeter

1. Introduction

Cold gas and dust in nearby elliptical galaxies was discovered only about 15 years ago. Compared to the cold ISM in spirals, the cold gas and dust is present in relatively small amounts and is seen in only 50% to 80% of nearby ellipticals. The source and content of the cold ISM in these galaxies is still uncertain, with optical and far-infrared dust-mass estimates differing by ∼10 to 100. Therefore, the present study aims to map and analyze emission from the cold dust of elliptical galaxies in order to probe and better constrain the dust and evolutionary properties of ellipticals.

We begin with a small sample of far-infrared (FIR) bright, nearby (less than 70 Mpc) ellipticals for which gas disks of CO emission have recently been resolved with interferometry of 7′′ spatial resolution (e.g. Young 2002; see left panel of Figure 1). Our observational study exploits the latest very sensitive submm array detectors (e.g., SHARC II at 350 μm on the CSO) with a goal of
providing the best submm (cold dust) distribution maps to date for our sample of galaxies (and for most in the sample the very first detections beyond 100 µm); dust temperature maps; gas-to-dust mass ratios; dust grain properties; dust association with other galactic structures; and constraints for models of dust evolution and generation in elliptical galaxies.

2. NGC 3656 and other Elliptical Galaxies in the Sample

The six galaxies in our sample are all ellipticals in that their luminosity profiles follow the de Vaucouleur law; however, they represent a spread of merger traces or ages, from galaxies that have been classified as on-going or early-age major merger (e.g. NGC 3656, Balcells et al. 2001) to very-late accretion or quiescent system (e.g. NGC 807, Murray et al. 2000). The FIR and submm mapping results (e.g. dust content) will be compared between the sample galaxies as a probe of not only dust but also of local merger-formation and evolutionary history of elliptical galaxies in general.

NGC 3656 is the far-infrared (FIR)-brightest elliptical in our sample. It has an optical elliptical body with an obscuring north-south, galactic minor-axis, edge-on gaseous dust lane (see right panel of Figure 1), two tidal tails, a system of shells and counter-rotating cores. These features together have been interpreted as evidence that the NGC 3656 system is an early major-merger remnant of disk galaxies (c.f. Balcells 1997, 2001). Central structures that are seen in unsharp-masked and residual galaxy-model K-band images of NGC 3656 have recently been interpreted as qualitative evidence that phase-mixing, since the disk-disk merger and subsequent violent relaxation of this galaxy, is incomplete (Rothberg & Joseph 2004).

Figure 1. Left: Total integrated CO(1-0) intensity map (white contours) of NGC 3656 with CO diameter of 34″ overlaid on optical data (gray scale and black contours) adopted from Young 2002. The white contours are in units of -5%, -2%, 2%, 5%, 10%, 20%, 30%, 50%, 70%, and 90% of 81.1 Jy beam$^{-1}$km s$^{-1}$ = 4.7 × 10$^{22}$ cm$^{-2}$ CO integrated intensity or column densities peaks (Young 2002). Right: An archival HST FW110 image overlayed with FW110-FW160 contours to depict the dust extinction in NGC 3656.
3. Archival HST and CSO observations of NGC 3656

The right panel in Figure 1 shows an HST FW110 image with FW110-FW160 (\(\sim J-H\) band) contours that demonstrate that the dust lane of NGC 3656 has the most extinction in a north-south region of radius \(\sim 5''\) with east-west asymmetry and a peak that is centered about \(1''\) east of the galactic nucleus (or the center of the dust lane). The asymmetry is consistent with the dust lane being seen edge-on and its nearside being on the galaxy’s eastern part.

Figure 2 shows a map of NGC 3656 from our exploratory CSO/SHARC II observations, during which we detected spatially-resolved, 350 \(\mu\)m continuum emission. The submm continuum of NGC 3656 has an unresolved core and extended emission that is slightly elongated north-to-southly down to the 50% contour level and within a radius of \(\sim 5''\). Beyond this it is detected with less certainty and has a generally bulging S-shape in the similar sense as seen in CO (1-0) and H-alpha images of the same region (see, e.g., left panel in Figure 1).

The extent of the resolved 350 \(\mu\)m emission down to the 50% contour level in NGC 3656 is consistent with a de-convolved Gaussian of FWHM of 8\(''\).1. This is about half the extent of the CO (1-0) emission observed in this galaxy. If one assumes the 350 \(\mu\)m emission is associated with the same dust as measured by IRAS at 60 and 100 \(\mu\)m, then our CSO results imply 29 K dust with an emissivity index of 1.6 and angular size of \(1.5 \times 10^{-9}\) steradians (see Figure 3).

Using the distance of 45 Mpc (e.g. Young 2002) and 350 \(\mu\)m dust absorption value of 0.192 m\(^2\)/kg (Draine 2003), a dust mass of \(1.4 \times 10^8\) solar masses is calculated for the temperature of 29 K and 350 \(\mu\)m integrated flux of 0.64 Jy.

4. Implications of the CSO and HST results of NGC 3656

Both the flux level and extent of the submm emission show that our 350 \(\mu\)m map of NGC 3656 cannot represent all the dust associated with the CO gas as resolved in this galaxy by Young 2002, if the normal gas-to-dust ratio (100) is...
used to estimate the dust flux level expected at 350 µm. The high extinction region of radius \( \sim 5'' \) seen in the HST colour map is roughly co-spatial with the high-brightness submm and radio regions respectively presented in this paper and by Mollenhoff et al. 1992, and probably represents a star-formation site and thus warmer and/or denser dust in NGC 3656. Our SHARC II data constrain the temperature of the remainder, more extended, dust distribution (associated with the more extended CO emission) to be less than 20 K. The current submm observations do not resolve the compact-core and extended-dust in NGC 3656; however, the fluxes of these components could be of comparable magnitude, originate from very distinct emission mechanisms, and thus impact their submm SED analysis, as is the case in the easier to spatially resolve, nearest merger-remnant elliptical Centaurus A (Leeuw et al. 2002).

The above results imply: (1) 350 µm observations are not just tracing cold dust, but also star-formation heating sources; (2) longer (and achievable) 350 µm SHARC II integrations are required to detect the cold dust emission at lower flux contours more closely associated with the CO and less heated by star-formation sites; (3) future mapping sampling colder and warmer dust respectively using SCUBA II/JCMT at 850 µm and HAWC/SOFIA at 88 and 155 µm or MIPS/Spitzer at 24 and 70 µm will be useful in de-convolving the star-formation heating effects from the dust distribution; (4) follow-up interferometry at submm, mm or high-frequency radio respectively with instruments such as SMA, CARMA, or VLA could also resolve the components of the cold dust, star-forming, and compact core (if it is distinct) at spatial resolutions comparable to the HST maps. Though our SHARC II observations are preliminary, the results already provide the best spatially resolved FIR-submm extent of this galaxy and of any elliptical > 40 Mpc to date, showing that dust of 29 K, probably heated by star-formation, exists out to at least \( \sim 1.8 \) kpc in NGC 3656.

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