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A unified image of dust grains for the warped spiral galaxy in the merger Centaurus A*

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Abstract. A unified view of dust grains of all sizes and temperatures in Centaurus A has been generated by combining ISOCAM mid-infrared images with optical data. In our unified V-15μm ratio image, a symmetrical bar-like structure and spiral arms of size 1.5 kpc surround the nucleus. We have overlaid the (H-K) model colour map of Quillen et al. (1993) and find a striking correspondence with the ridges seen in emission 15 μm and the dark lanes which they find in the near-infrared. The inference is that the morphology of large cold dust grains, responsible for the extinction at V, H and K, closely follows that of the hot dust over the full projected 3kpc diameter of the mini-spiral galaxy. From the spatial distribution of our V-15μm map, we derive a dust mass of approximately $2\,10^6$ $M_\odot$, similar to the dust mass of the Triangulum galaxy NGC 598 (M33). A further intercomparison of optical and ISO images reveals that the morphology of the warp of the central spiral may be optically traced: the contours of an entire one half of the spiral lie on the same warped ridge as that found in optical photographs.

Key words: galaxies: individual: NGC 5128 – ISM: dust, extinction – infrared: ISM: continuum – infrared: ISM: lines and bands

1. Introduction

An object of intense astrophysical interest is our closest active radio galaxy, Centaurus A (NGC 5128), only 3.25 Mpc distant. Its complex and intruiging optical structure was noted as early as 1847 by Sir John Herschel, working at the Cape of Good Hope. In the *Hubble Atlas*, Centaurus A is classified as the possible merger of an elliptical galaxy with a spiral galaxy, following the earlier suggestion by Baade & Minkowski (1954) that NGC 5128 represents two galaxies in collision.

Centaurus A has been imaged with the Infrared Space Observatory (ISO, Kessler et al. 1996) at wavelengths of 7 and 15 μm (Mirabel et al. 1999), to reveal the emission of very small dust grains and of macromolecules. The galaxy has also been optically imaged at the prime-focus of the 4-m Cerro Tololo reflector, to probe the large dust grain distribution.

Indeed, the smallest dust grains (radii 0.01 μm and less) which may transiently be very hot (up to $\sim$ 1000 K) and readily observed by the Infrared Space Observatory in the mid-infrared, contribute little to the extinction at optical wavelengths. Mid-infrared ISOCAM images (Cesarsky et al. 1996) do not trace the distribution of the large ($\sim$ 0.1 μm) grains, which however dominate the extinction in visible light.

As reviewed by Greenberg & Li (1996), the large (tenth micron) grains are essentially *always* cold; they would need to be placed at a remarkably short distance of only 0.1 parsec from the intense radiation of an O5 star before the ice would evaporate. Indeed, these large grains are typically too cold (T $\sim$ 20 K in the diffuse ISM, Block 1996) to be observed in emission shortward of 100 μm, so these dust grains were systematically missed by the Infrared Astronomy Satellite IRAS (see Sauvage & Thuan 1994). Yet it is these grains which we see in any Atlas photograph of a dusty galaxy.

In order to probe the distribution of dust grains of all sizes and temperatures, we have developed a unified method by combining optical with ISOCAM mid-infrared images. An example of this technique has already been applied to the Whirlpool Galaxy M 51 (Block et al. 1997). Such a methodology shows the large, cold dust grains in extinction and the very small hot grains and macromolecules in emission (negative extinction), so that optical minus mid-infrared imaging enhances all populations of dust grains and of macromolecules (Block et al. 1997).

2. The V-15 μm morphology of Centaurus A

Some of the most dramatic and chaotic dust lane morphologies are to be found in optical photographs of our closest radio galaxy, Centaurus A. This is exemplified on Fig. 1 which represents an overlay of ISOCAM LW3 15 μm contours superposed on the V-band prime focus image of Centaurus A. The mid-infrared structure has been interpreted as tracing dust in a barred mini-spiral galaxy (Mirabel et al. 1999), reformed from the interstellar medium of the accreted galaxy.

In Fig. 2 we present a ratio image, secured by dividing the ISOCAM image by the optical one. The optical image was re-

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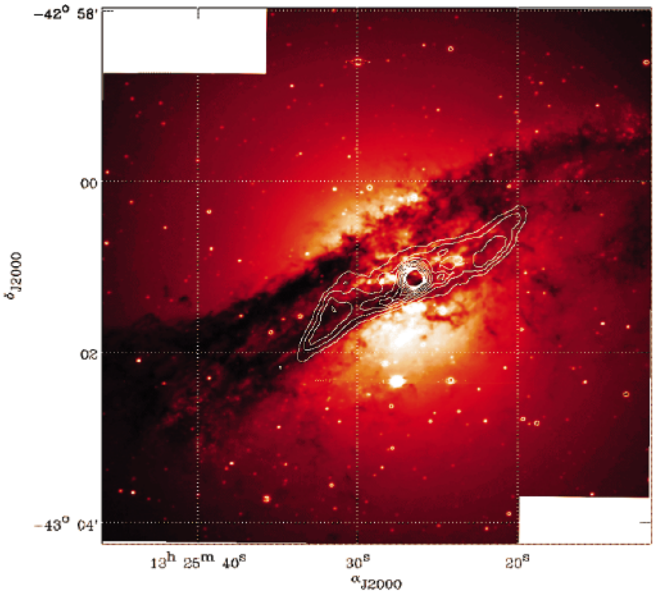

Fig. 1. A contour overlay of the 15 μm warped disk detected in emission by ISOCAM on an optical V-band CCD image of Centaurus A, secured at the prime focus of the 4-m reflector at Cerro Tololo. North is up, and east to the left. The southern contours of the central warped disk strikingly follow the interface of optical extinction/emission both to the SE and NW over the full 3 kpc projected diameter of the disk.

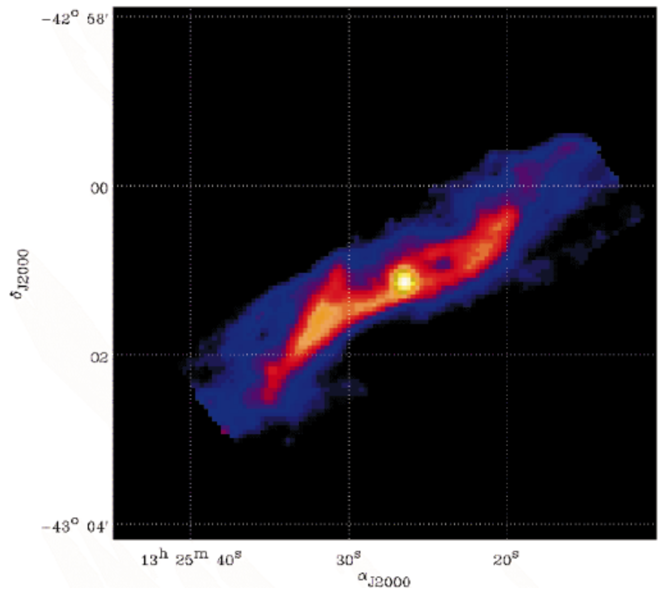

Fig. 2. A V-15 μm ratio image shows a unified view of macromolecules, very small grains and large dust particles at the centre of Centaurus A. A symmetrical disk structure of radius 1.5 kpc – colour coded orange-red – surrounds the nucleus. The disk, postulated to be the remnant of a small spiral galaxy involved in the merger with the giant elliptical, contains both very small dust grains (detected in emission at 15 μm by ISOCAM) and large cold dust grains, whose morphology is almost identical to the dark lanes detected by Quillen et al. (1993) in their H-K colour models. Other dust lanes which give Centaurus A its rather chaotic appearance have no 15 μm emission counterpart and are colour coded blue in this figure.

binned and convolved with the ISOCAM LW3 point spread function as fully described by Block et al. (1997). Several key features in these figures are worthy of note:

Firstly, an inner disk-like structure of dust of radius 1.5 arcmin (or 1.4 kpc at 3.25 Mpc) is clearly unveiled in our V-15 μm image. The disk is bright, being detected *in emission* at 15 μm and *in extinction* at V. It is quite symmetric, clearly showing the bar arms on both sides of the nucleus connecting to the spiral arms (see Mirabel et al. 1999). At the edges, the disk starts to warp. The western side of the bar shows less clearly than the eastern side, possibly indicating that this is the far-side of the structure (extinction will be less on the far-side thus breaking the symmetry of the emission structure).

There is a striking correspondence with the bright structures seen in our Fig. 2 and the dark lanes which Quillen et al. (1993) find in the H-K near-infrared regime, especially on the SE side, confirming that this should be the near side of the mini-spiral. The somewhat poorer agreement on the NW sides probably originates in the fact that modelling in Quillen et al. (1993) did not take into account the existence of a bar structure in the dust disk, which introduces a strong asymmetry in the azimuthal distribution of the dust: on the NW side, most of the dust is on the far-side of the disk, thus contributing little extinction (see Fig. 2). Nevertheless, the rather good agreement between emission and extinction structures suggests that the distribution of large, cold dust grains in the disk (responsible for the extinction at V, H and K) should closely follow the morphology of hot grains detected in emission by ISOCAM. This is now independently confirmed by the SCUBA observations of cold dust detected in emission at 850 μm and reported by Mirabel et al. (1999, see their Fig. 2).

There is a also a close similarity between the morphology of the disk seen in our V-15 μm image and the warped disk inferred from molecular gas CO(2-1) observations (eg. Fig. 10 in Quillen et al. 1992). These morphological considerations offer strong support – apart from kinematical data presented by Mirabel et al. (1999) – to believe that this gas+dust structure represents the disk of a mini-spiral galaxy reformed during the merger of a companion galaxy with the giant elliptical.

In our V-15 μm image, very small dust grains have presumably been subject to temperature spiking. There is a significant amount of UV emission from newly formed stars in the ionized gas disk (Marston & Dickens 1988, Nicholson et al. 1992) and the similarity with the molecular gas distribution likely indicates that the dust seen in emission at 15 μm resides at the interface of UV irradiated clouds.

Secondly: it is remarkable to see just how closely the southernmost contours of the disk *follow the ridge of optical emission* both to the SE and to the NW over the full 3 kpc projected diameter of the disk. The southernmost sector of the disk of the small spiral galaxy reformed in the merger can actually be optically delineated: that there indeed has been a piling up of dusty material on the SE ridge is confirmed by dark lanes seen in the near-infrared images of Quillen et al. (1993, see especially their Fig. 11).

The presence of dark dust lanes at K is indicative of appreciable optical depths, since imaging at the K-band (2.16 μm) penetrates dust ten times more efficiently than does visible light. The various components of extinction have been recently reviewed by Bryant & Hunstead (1999) from NIR imaging and spectroscopy of the central 30″ of the galaxy. They show that extinction to the K-band point source is smaller than 10 mag in V, compatible with, for instance, the extinction that could be derived ($\sim$ 3 magnitudes in V) to the line of sight of SN1986G (Phillips et al. 1987). They also clearly demonstrate that the K-band source is unlikely to be the AGN itself, but rather dust clouds located less than 20 pc away from it. This explains why much higher extinctions have been reported (e.g. 70 V mag from X-ray studies, see the discussion in Packham et al. 1996): the latter likely samples the line of sight all the way to the AGN, while the former does not include that occuring in a very compact circumnuclear ring.

In the NW there is diffuse optical emission covering a sector of the 15 μm emission, which could, in part, be attributed to forward scattering by dust grains, toward the observer, from the central engine of Centaurus A. Other dust lanes which give Centaurus A its rather chaotic appearance have no 15 μm emission counterpart and are colour coded blue in Fig. 2 (this is specifically the case of the north-eastern dust lane which forms the northern boundary of the optical dust lane). Note that these regions also lack counterparts in the SCUBA maps of Mirabel et al. (1999). This is quite puzzling given their optical appearance, and is worth elucidating. Indeed, looking at the near-infrared maps of Quillen et al. (1993), one can see that the north-eastern lane is still detectable in the K-band image and that it has a (J-K) color similar to that of the more central dust lane that we also see in emission. Therefore the total optical depths of the two lanes are likely of the same order of magnitude and, were the cold dust temperatures to be of the same order, one would expect to detect the northern lane in the submillimeter. The answer most probably lies in the actual three-dimensional location of the dust giving rise to that lane, i.e. it should be further away from the nucleus of Centaurus A. As mentionned earlier, the current view of the dust structure in Centaurus A presented by Mirabel et al. (1999) and supported by the present paper does not contradict the geometrical model developped by Quillen et al. (1993). We can therefore use that model to find the actual location of the northern dust lane. According to Quillen et al. (1993) strong extinction will occur at folds in the warped disk or tilted rings structure. At these folds, the line of sight becomes tangential to the structure, thus maximizing the optical depth of the dust. Using the parameters presented by Quillen et al. (1993) we compute the angle between the line of sight and the axis of the concentric rings as a function of distance to the nucleus. Extremas in this function will signal the presence of the folds we are searching for. We find two such extremas, the inner one corresponding to the inner dust lane that we also see in emission, and the second one $\sim$ 3 times further away, that gives rise to the north-eastern dust lane. This significant increase in distance is very likely to be the reason why the north-eastern dust lane has no emission counterpart: at that distance, heating by the stellar population of the giant elliptical is probably too low, and, since star formation activity, as traced by the ISOCAM emission, has ceased, internal heating sources are absent.

We can actually quantitatively check that cold dust can give rise to strong extinction feature while escaping submm detection: if we assume a Galactic gas-to-dust mass ratio of 160, and $A_V/N(HI) = 5.34\,10^{-22}$ mag cm^2 from Bohlin et al. (1978), we can compute the relation between the extinction and the emission. To simplifiy this computation, we use dust grains of a single size, and a single density, emitting as modified blackbodies. This gives:

$$A_v = 1.98\,10^{-1} \left(\frac{F_\nu}{1\,mJy.''^{-2}}\right) \left(\frac{\rho}{10^{-12}\,g.\mu m^{-3}}\right) \left(\frac{a}{1\,\mu m}\right) \left(\frac{\nu}{10^{11}\,Hz}\right)^{-3} \left(\frac{1}{Q_{abs}(\nu,a)}\right) \left[\exp\left(4.8\left(\frac{\nu}{10^{11}\,Hz}\right)\left(\frac{1\,K}{T}\right)\right) - 1\right] \quad (1)$$

From the SCUBA 450 μm image of Mirabel et al. (1999), we derive an upper limit for the flux in the dark lane region of 2 mJy.″^{2}. Using a typical size of 0.1 μm for the grains, and a temperature of 15 K for the cold dust, known ranges of grain properties (Draine & Lee 1984, Mennella et al. 1998), translate in A_V of typically 5-20, amply enough to produce the very dark lane observed in north-east side of the galaxy. This range of extinction values fits well with the fact that the NE dust lane has colors similar to the central dust lane (Quillen et al. 1993) and that the extinction in the central region (excluding that occuring in the immediate vicinity of the AGN) is $\leq$10 mag in V (Bryant & Hunstead 1999).

3. The dust mass and survival of dust grains in the merger event

It is instructive to estimate the mass of dust associated with the mini-barred spiral. From our V-15 μm image, we estimate the thickness of the emission structures (bar and spiral arms) to be 12″ corresponding to only 190 parsecs. From Fig. 2 we see that the spiral arms start at 1.5 kpc from the nucleus and that all structures, bar and arms are $\sim$200 pc wide. From Fig. 3 of Mirabel et al. (1999) we can see that the spiral arms subtend at least 45°. If we use a surface atomic gas mass density of $\sim$ 80 solar masses per square parsec (appropriate to an atomic hydrogen column density of $\sim 10^{22}$ atoms cm^{-2} as observed by van Gorkom et al. 1990) we derive an atomic hydrogen gas mass of $1.4{\times}10^8$ solar masses. The uncertainty is a reduction by a factor of $\sim$ 4: for a warped disk the line of sight can penetrate the disk several times, and the actual HI surface density will be that many times less. Eckart et al. (1990) use a line-of-sight penetration of four times. Furthermore, the integrated molecular gas mass (Eckart et al. 1990) is almost identical to that of the atomic gas mass, so we derive a total combined atomic and molecular gas mass of 2.8×10^8 solar masses. If we adopt a canonical gas-to-dust ratio of 100, we derive a dust mass of 0.7–2.8×10^6 solar masses. Such a dust mass is typical for a small spiral galaxy such as M33 or for dusty ellipticals. Typical ranges in dust masses for bright nearby ellipticals detected by IRAS are in the 10^4 – 10^6 solar mass (Goudfrooij 1996).

Our estimate for the dust mass excludes the mass of dust grains found at larger galactocentric radii which have no ISOCAM emission component. It also excludes dust grains residing in the disk of the mini-barred spiral and responsible for the diffuse emission seen in Fig. 1. This likely explains why our dust mass estimate is a factor of $\sim$10 smaller than that of Mirabel et al. (1999) using IRAS and SCUBA data. These latter instruments detect a larger fraction of the complete dust emission, not only that residing in the bar+arms struture.

Dynamical studies can be used to study the problem of dust survival in a merger event. Nicholson et al. (1992) propose that the ionized gas disk has completed more than 10 rotations (each $\sim 1\times10^8$ year at 3.0 kpc) since the merger event (Rix & Katz 1991). It is believed (Nicholson et al. 1992) that the merger and subsequent formation of the dust band occurred $\sim 10^9$ yr ago. A dynamically evolved structure is also attested to by the well established star formation seen throughout and by the distribution of stellar shells (Malin et al. 1983) within the elliptical component of Centaurus A. Quillen et al. (1993) have constructed models wherein a warped disk evolving as a result of differential precession in a prolate potential gives an excellent fit to their infrared data. If the structure is 10^9 yr old, the inner 1.5 kpc disk, having completed $\sim$ 20 rotations, may have had time to settle into a preferred plane of the host elliptical (Steinman-Cameron & Durisen 1982). The typical lifetime of a dust grain in the absence of shock induced destructive mechanisms is of the order of 10^9 years and mergers would not destroy dust grains unless very strong shocks are involved. Those grains which remain in giant molecular clouds would in any case be shielded from destructive processes (Greenberg, private communication).

4. Conclusion

The importance of studying the unified distribution of dust grains is clear. In Centaurus A, where the overall extinction is asymmetric and rather chaotic, lies embedded a beautifully symmetric barred mini-spiral. This specific case illustrates particulary well the importance of obtaining information on dust grains of all sizes to clearly understand the large scale distribution of dust: if the spiral were to be seen face-on, the column densities at equivalent galactocentric radii would then essentially be the same. However, if one tilts a barred spiral embedded in light sources (stars and an active galactic nucleus), a break in symmetry is introduced by projection effects as different positions on the spiral now lie at varying optical depths in the line of sight. That an intrinsically symmetric dust distribution can produce an extremely asymetric dust lane has been clearly demonstrated by Elmegreen & Block (1999).

In Centaurus A, we have shown that the V-15 bright structures are very well correlated with the H-K model color maps of Quillen et al. (1993). We note that this correlation is much better in the SE side than in the NW side, indicating an asymmetry in the distribution of the dust in the disk plane that is not taken into account by the models. This asymmetry is very well understood if the dust is distributed in a bar+arms structure as evidenced by Mirabel et al. (1999).

Detailed comparison of the emission and extinction structures also reveal that the warp observed in the emission map closely follows the southern ridge of extinction, implying that the plane of the mini-barred galaxy disk is nearly perpendicular to the plane of the sky on approximately 2–3 kpc.

Finally a dust mass can be computed assuming that the dust resides mostly in the bar+arms structure. The result, $\sim2\times10^6\,M_\odot$, though compatible with the dust mass of a small spiral or that found in elliptical galaxies, is markedly smaller than that derived by Mirabel et al. (1999). We interpret this result as implying that a substantial amount of dust is diffuse and resides in the disk of the mini-barred spiral galaxy.

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