WARPED DUST LANES IN ELLIPTICAL GALAXIES: TRANSIENT OR STATIONARY PHENOMENA?¹

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ABSTRACT

Spectroscopic observations of NGC 5128 show that the stellar component possesses a velocity gradient along its major axis with a total velocity difference of 160 km s^{-1} . This velocity, together with a velocity dispersion of 140 km s^{-1} , places NGC 5128 among the fast rotating elliptical galaxies. We find that the motion of the warped dust lane with respect to that of the stars is direct. Prograde motions are also found in the warp of the E4 Anon 0151–498, while we report observations of a warped dust lane with retrograde motion in the E3.5 NGC 5363. We analyze the conditions under which the warped configurations in these galaxies are transient or stationary. The intrinsic shape of these systems is also discussed.

Subject headings: galaxies: internal motions — galaxies: structure

I. INTRODUCTION

The existence of a class of elliptical galaxies with dust lanes across their minor axes has been pointed out by Bertola and Galletta (1978). They suggested the possibility of inferring the intrinsic shape of the stellar body from the orientation of dust lanes. A prototype of this class of objects is the nearby and well-known elliptical galaxy NGC 5128 (Cen A). A survey by Hawarden *et al.* (1981) identified a large number of elliptical galaxies with dust lanes along the major, minor, or a skew axis. Since then several studies have examined the possible configurations of a dust and gaseous component in the oblate, prolate, or triaxial potential of a stellar body, which could be also tumbling around one principal axis (Tubbs 1980; Tohline, Simonson, and Caldwell 1982; van Albada, Kotanyi, and Schwarzschild 1982; Merritt and de Zeeuw 1983; Lake and Norman 1983; Steiman-Cameron and Durisen 1982, 1984).

In particular, Tubbs (1980) has computed a model for NGC 5128 where the dust lane is the result of a collision of a stationary prolate elliptical galaxy with a small gas-rich system whose orbital plane is originally inclined at 30° to the symmetry plane of the galaxy. This is the angle observed between the inner and outer dust lane orientation. The infalling galaxy is disrupted, and the gas settles toward the symmetry plane, the central parts being the first to align with it. When the galaxy is viewed along a particular line of sight lying near the symmetry plane, the dust lane appears along the minor axis while the as yet unsettled outer parts produce the characteristic warped shape of the dust lane. The inferred age of this transient

phenomenon is 3×10^8 yr. An improved version of this model has been produced by Simonson (1982).

An alternative model has been proposed by van Albada, Kotanyi, and Schwarzschild (1982) who interpret the warped dust lane as a stationary phenomenon in a triaxial galaxy tumbling about the minor axis. They found that stable orbits lying near the plane perpendicular to the major axis are inclined due to the tumbling. The inclination is an increasing function with the distance from the center. The resulting configuration is again warped when viewed near the intermediate axis. This stationary situation requires that the motion of the gas in the warps is opposite to the rotation of the figure. This constraint for the motion of the gas with respect to the tumbling, if any, is not required if the warps are due to not yet settled material acquired from outside.

In order to become oriented between these two possibilities, observations of the dynamics of both the stellar and the gaseous/dusty component are crucial. The rotation of the ionized gas within NGC 5128 has been recently measured by Graham (1979), Appenzeller and Möllenhoff (1980), Möllenhoff (1981), Marcellin *et al.* (1982), and Phillips *et al.* (1984). All these measurements indicate the presence of a strong velocity gradient of the gas along the minor axis, the receding side being the northwest one. An attempt to map the velocity field of the stellar component made by Graham (1979) has given no positive results with a limit of 30 km s^{-1} within $1'$ of the nucleus, while very preliminary results on the velocity field of the stellar body were reported by Bertola, Galletta, and Zeilinger (1983), Davies *et al.* (1984), and Fosbury *et al.* (1984). In this *Letter* we describe a successful attempt to detect a velocity gradient along the major axis of

¹Based on observations collected at the European Southern Observatory, La Silla, Chile.

the galaxy, indicating stellar motions which are prograde with respect to the direction of the gas motion in the warps. The same kinematical situation is found in Anon 0151–498, an E4 galaxy with a warped dust lane along the minor axis. In addition, we report the presence of warps on both sides of the dust lane of the elliptical galaxy NGC 5363. This is the first case in which the direction of the motion of the gas in the warps is retrograde with respect to the direction of the motions in the stellar component.

II. OBSERVATIONS AND RESULTS

A survey of the stellar kinematics of NGC 5128 was started in 1979, with the IDS + Boller & Chivens spectrograph at the 3.6 m ESO telescope. We set one aperture at 70'' northeast of the nucleus along the major axis of the galaxy and exposed for 2 hr using a dispersion of $29 \text{ \AA mm}^{-1}$. Successively, in 1982 March and 1984 March we obtained five spectra of the galaxy NGC 5128 (J3745E, G, J3758A, C, J4764A), two along the major axis at P.A. = 35° , one along the dust lane and two at intermediate position angles (P.A. = 80° , 170°), with the same spectrograph and image tube mounted to the Cassegrain focus of the 1.52 m ESO telescope. The exposure times ranged from 40 to 90 minutes. The dispersion of these spectra is $39 \text{ \AA mm}^{-1}$, while the plate scale perpendicular to the dispersion is $87'' \text{ mm}^{-1}$. We profited from the large size of the slit ($5''$) at the 1.52 m telescope which provided the ability to explore NGC 5128 over a wide extent.

On each night at least two template spectra of slowly rotating giant stars of spectral type ranging from late G to early K were secured with the same instrument. All plates were digitized using the Vienna Observatory PDS microdensitometer and further reduced using the IHAP software package at the ESO headquarters in Garching. The resulting images were analyzed at the Padova Observatory using the Fourier quotient technique in the spectral range $\lambda\lambda 3900\text{--}4500$ (Bertola *et al.* 1984). A similar reduction procedure was applied to the $\lambda\lambda 4800\text{--}5200$ IDS spectrum. The final rotation curve, velocity dispersion, and line strength profiles of NGC 5128 derived from the two spectra along the major axis and the IDS measurement are plotted in Figure 1. In addition, the $\lambda\lambda 3727\text{--}3729$ doublet has been measured on the minor axis spectrum with the ESO Grant machine.

From these observations we make the following findings:

1. A velocity gradient is definitely present along the major axis (P.A. = 35°) of the galaxy, and the southwest side is receding. The peak-to-peak velocity difference is 160 km s^{-1} over a region of $\pm 110''$ from the nucleus. This gradient is confirmed by the spectra taken at P.A. $\pm 45^\circ$ from the major axis, which seems to indicate cylindrical rather than spheroidal rotation (Binney 1980) up to $50''$ from the major axis.

2. The velocity dispersion is approximately constant at the value of $\sigma = 140 \text{ km s}^{-1}$ over the observed region. However, there is a slight difference of 25 km s^{-1} in the mean value of the two sides. The corresponding value of V_{max}/σ is 0.57. We find an absolute magnitude $M_B = -20.5$ based on the distance $D = 5 \text{ Mpc}$ and $B = 7.96$ (de Vaucouleurs, de Vaucouleurs, and Corwin 1976) and an ellipticity of $\epsilon = 0.3$ (Bertola and Galletta 1978). When plotted in the $\log(V_{\text{max}}/\sigma)$ - M_B , $\log \sigma$ - M_B , and V_{max}/σ - ϵ diagrams (Davies *et al.* 1983),

NGC 5128 shows all the characteristics of an elliptical with a significant amount of rotation. Our values of ΔV and σ seem to be in agreement with those announced by Davies *et al.* (1984). As far as the gas component is concerned, we measure a constant gradient of $2 \text{ km s}^{-1} \text{ arcsec}^{-1}$ out to about $120''$ from the nucleus, in agreement with previous studies cited above, the northwest side being the receding one.

III. DISCUSSION

a) NGC 5128

Several conclusions can be drawn from the observational results on this galaxy:

1. The stellar velocity gradient, which is comparable (~ 0.3 times) to that of the gas, is too high to be mainly due to figure tumbling around the minor axis. If this were true, gas could not settle into a plane perpendicular to the major axis due to the nonstatic nature of the potential (Tohline and Durisen 1982). Therefore the observed gradient must be due mainly to streaming motions.

2. The presence of a significant stellar velocity gradient due to the streaming motions along the major axis, which give rise to $V_{\text{max}}/\sigma = 0.57$, eliminates the possibility that the galaxy is prolate (Richstone and Potter 1982). The oblate configuration also has to be ruled out, since material in an inclined orbit is expected to settle into the equatorial plane or, if captured in polar orbit, to give rise to a rather distorted dust lane with a break in the center (Lake and Norman 1984). Thus we are left with a triaxial configuration for NGC 5128.

3. If the warping phenomenon in NGC 5128 is due to slow tumbling, we are looking at it close to the intermediate axis (van Albada, Kotanyi, and Schwarzschild 1982; Merritt and de Zeeuw 1983). The same conclusion can be reached in the alternative case in which the gas is on its way to settle on a preferred plane. In fact, since the central dust layer, which first reaches the stability, is observed on edge, the line of sight must be contained in the plane defined by the minor and intermediate axes, which is one of the preferred settling planes in a triaxial galaxy. In addition, the presence of a significant stellar streaming along the major axis indicates that we are viewing the galaxy closer to the intermediate than to the minor axis (Miller and Smith 1979; Schwarzschild 1982). As a consequence, in the following we shall assume that the observed flattening (0.7) of NGC 5128 is equal to the ratio of the intrinsic minor to the major axis of the triaxial configuration.

4. From the direction of the warps and the direction of rotation of the gas in the warps combined with the now known direction of rotation of the stellar component, it appears that the gas motion in the warps is prograde when compared to the motion of the stellar component. A similar observational situation has been described by Caldwell (1984) in NGC 5266.

b) Anon 0151–498

In addition to NGC 5128 and NGC 5266 we would like to point out another case with warps in prograde motion, namely Anon 0151–498. This galaxy has a dust lane across the minor axis which bends toward the southwest on its west side

FIG. 1.—Kinematical data for NGC 5128 (major axis). The “line strength” γ (upper panel), the velocity dispersion σ in km s^{-1} (middle panel), and the radial velocities V vs. the distance from the center (bottom panel) are plotted. The center corresponds to the position of the nucleus as defined by Möllenhoff (1981). Plate number, exposure times, and IDS observation are indicated. The γ values plotted are only from the more extended spectrum (J3745E). The error bars for the single measurements come from the Fourier quotient fit procedure.

(Hawarden *et al.* 1981; see also the photograph published by Bertola (1981). In fact, the stellar and gaseous motions (Sharples *et al.* 1983) and their directions (Sharples (1984) show that the stellar motions are receding on the north side, while the gas is receding on the east side. This intrinsically bright galaxy ($M_B = -22$; Sharples *et al.* 1983) shows all the properties of a slowly rotating elliptical (Davies *et al.* 1983).

c) NGC 5363

The galaxy NGC 5363 is another of the original examples of an elliptical with a dust lane along the minor axis (Bertola and Galletta 1978). An image of this galaxy has been obtained by J. S. Gallagher with the 2.1 m telescope of the NOAO with the video camera detector and kindly put at our disposal. With high-frequency enhancement, the image reveals a structure that we interpret as a strongly warped dust lane. In the southwest side at about $3''$ from the center, the dust lane bends toward the southeast and extends $13''$, running parallel to the major axis. The opposite side is symmetric but less

extended. Since the effective radius of NGC 5363 is $27''$ (de Vaucouleurs, de Vaucouleurs, and Corwin 1976), the dust lane is limited to the central region of the galaxy, unlike NGC 5128 where the dust extends up to the effective radius.

In addition to the velocity curve of Bertola and Galletta (1978) along the major axis (P.A. = 130°) derived both from the emission and absorption lines, more extended velocity curves and velocity dispersion profiles were produced by Sharples *et al.* (1983). The mean velocity dispersion of the stars is about 200 km s^{-1} , and the corresponding V_{max}/σ is 0.67. According to Bertola and Galletta (1978) and Sharples (1984), the receding side is the southeast one. Sharples *et al.* (1983) also measured the velocity gradient along the minor axis, detecting a maximum rotational velocity of 90 km s^{-1} in the gas at $5''$ from the nucleus, the northeast side being the receding one (Sharples 1984). The ratio between the angular velocity of the gas and of the stars is about 1.1.

The close resemblance of the morphological and kinematical properties of NGC 5363 with those of NGC 5128 leads to the same results as far as orientation of the galaxy, triaxial

shape, and lack of significant tumbling are concerned. In contrast to the cases of NGC 5128, Anon 0151–498, and NGC 5266, this is the first case of an elliptical galaxy with the dust lane along the minor axis showing retrograde motions in the warps with respect to the observed stellar motions. A confirmation of this fact is the negative velocities on the southeast side of the major axis rotation curve of the gas (Bertola and Galletta 1978), which now finds an explanation because the spectrograph slit crosses the approaching southwest warp.

The value of $M_B = -20.6$, based on a distance of $22.4 (H/50)^{-1}$ Mpc and $B = 11.2$ (de Vaucouleurs, de Vaucouleurs, and Corwin 1976) and those of σ and $V_{\max}$ also place this E3.5 galaxy (de Vaucouleurs, de Vaucouleurs, and Corwin 1976) among the fast rotating ellipticals (Davies *et al.* 1983).

At this point it is interesting to investigate the role of the above results in connection with the transient (Tubbs 1980; Simonson 1982) or stationary (van Albada, Kotanyi, and Schwarzschild 1982) nature of the warps. The observations showing that the motion of the gas in the warps is either prograde (NGC 5128, Anon 0151–498, NGC 5266) or retrograde (NGC 5363) with respect to the observed stellar motions (streaming plus possible tumbling) find an easy explanation in terms of the warps being a transient feature produced by a recent capture of gas.

On the contrary, in order to satisfy the stationary model, one has to admit (1) that slow tumbling of the figure around the minor axis is present and (2) that this tumbling is retrograde with respect to the motion of the gas in the warps when seen close to the intermediate axis. This requires that a considerable amount of counterrotation of stars with respect to the tumbling is present in NGC 5128, Anon 0151–498, and NGC 5266, while direct streaming motions are predominant in NGC 5363. Figure rotation in the same sense as the stellar streaming motions is indicated by the model of Miller and Smith (1979), de Zeeuw and Merritt (1983), Lake and Norman (1984), and Merritt and de Zeeuw (1983). However, some models (Freeman 1966; Vandervoort and Welty 1982; Vietri 1985) seem to support the possibility of retrograde stellar streaming.

It should be remarked that the transient model of Tubbs (1980) and the stationary model of van Albada, Kotanyi, and Schwarzschild (1982) could not be alternative, in the sense

that the first one describes the early stages of an acquisition process, which after an appropriate time could reach the situation described by the second one, if slow tumbling is present. In fact, both the transient and the stationary situations are consistent with an acquisition process which for NGC 5128 and other dust lane ellipticals is also indicated by the presence of shell structures (Malin, Quinn, and Graham 1983; Schweizer 1983).

An indication of the intrinsic axial ratios of these galaxies can be obtained using the relation derived by Binney (1978) among the three quantities $V_{\max}/\sigma$, b/a , and c/a , where a , b , and c are the major, intermediate, and minor axes of a triaxial density distribution, under the assumption of velocity isotropy. Applying this relation to NGC 5128 one finds $b/a = 0.8$. If the warps are transient, a different approach to the intrinsic shape of NGC 5128 is provided by assuming that the warp angle (30°) is close to the inclination of the axis of the gas orbit at acquisition with respect to the long axis. According to relations (5) and (8) given by Steiman-Cameron and Durisen (1982), one finds that b/a is in the range defined by $b/a = c/a = 0.7$ (prolate case) and the upper limit $b/a = 0.93$. If the warps are stationary, information on the shape of the galaxy can be obtained by detailed model calculations. In the case of Anon 0151–498, the low value of $V_{\max}/\sigma$ (0.2; Sharples *et al.* 1983) is consistent with a prolate or almost prolate structure (Binney 1978; Richstone and Potter 1982). For NGC 5363, assuming $c/a = 0.65$, its $V_{\max}/\sigma$ value is consistent with a triaxial isotropic galaxy whose b/a is 0.85. On the other hand, if the warps are transient features, the alignment of the dust lane with the major axis in the outer regions indicates that the orbital angular momentum of the captured material has experienced a strong deviation toward the major axis, which can be produced only by an almost prolate potential.

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