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A COMPANION NUCLEAR BULGE TO THE SEYFERT RING GALAXY NGC 985[1]

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ABSTRACT

Subarcsecond optical broad band images of the Seyfert galaxy NGC 985 are presented. A second nucleus located 3.8″ NW of the Seyfert nucleus is clearly revealed by these images and confirmed by the study of its colors and brightness profile. We claim that this object is a spheroidal bulge with an absolute magnitude $M_B = -16.6$, and that it is responsible for the peculiar ring shape of NGC 985. We also find that many knots of star formation spread throughout the ring are all coeval. © *1996 American Astronomical Society.*

1. INTRODUCTION

The galaxy NGC 985 (Mrk1048, VV285) is a morphologically peculiar object showing two clearly distinct and powerful zones of emission, namely the active nucleus— NGC 985 was classified as a Seyfert 1 galaxy by De Vaucouleurs & De Vaucouleurs (1975)— and a ring-shaped structure quite conspicuous in optical and infrared images where active star formation is taking place (Rodríguez Espinosa & Stanga 1990, hereafter RES; Appleton & Marcum 1993, hereafter AM).

NGC 985 is a strong UV and x-ray source (Wu *et al.* 1980, 1983; Ghigo *et al.* 1983). The Seyfert nucleus dominates the galaxy at these wavelengths, as well as in the optical (RES) and far IR wavelengths (Appleton & Struck-Marcell 1987a). NGC 985 has also been measured with the VLA (Ulvestad & Wilson 1984), although the radio source has not yet been properly resolved.

Detailed optical studies of the nucleus and the surrounding ring have been carried out by Rodríguez Espinosa & Stanga (1990), and Stanga *et al.* (1991). These authors obtained images of the galaxy as well as several spectra across the Seyfert nucleus and along the arm which extends westwards from it, showing that together with a powerful Seyfert nucleus, which exhibits broad lines with more than 12000 km/s FWHM, there is an extended zone of Hα emission produced by a host of giant H II regions scattered throughout most of the so called ring. AM have also performed a careful study of NGC 985 in the near-IR, where they have detected many IR knots spread out throughout the ring-like structure. Some of these IR knots do coincide with knots seen in Hα by RES.

It has been proposed that ring galaxies result from the collision between two spiral disks (Lynds & Toomre 1976; Appleton & Struck-Marcell 1987b; Hippelein 1989). Indeed NGC 985 has the appearance of a galaxy having undergone strong tidal disruptions very likely due to a galaxy encounter, although an external nearby companion galaxy has not been found. Rodríguez Espinosa & Stanga (1990) noted the existence of a protruding assymetry in the nebulosity surrounding the Seyfert nucleus in a continuum optical image of NGC 985, and hinted the possibility that it was due to a second nucleus located a few arcseconds NW of the point-like Seyfert nucleus. Appleton & Marcum (1993) have obtained high resolution IR images that also show the presence of an object near the Seyfert nucleus. These authors gave IR colors for this source which they hinted as a possible nuclear source. Furthermore, after removal of an $r^{1/4}$ bulge emission associated with the Seyfert nucleus, AM concluded that this second source lies at the end of a linear feature which they interpreted as an IR bar followed by a tightly wrapped spiral arm, further supporting the extragalactic nature of this second source.

In this paper, we present sub-arcsecond resolution optical images of NGC 985, which clearly show the existence of this companion object 3.8″ NW of the Seyfert nucleus. We present an analysis of its colors and brightness profile, as well as of the colors of other emitting regions present in the galaxy. Our data provide definitive proof of the fact that this companion object has colors and shape compatible with being the bulge of a spheroidal galaxy. Thus, we claim that NGC 985 is a composite system of two galaxies, whose peculiar morphology is a consequence of the interaction between them.

2. OBSERVATIONS

Broad band optical images of NGC 985 were acquired at the Nordic Optical Telescope (NOT), sited at the Observatorio del Roque de los Muchachos on the island of La Palma, Spain, on 1992 September 4, with the Stockholm CCD camera in its standby position. Broad band *B, V,* and *R* filters were used. The resulting telescope-CCD camera configuration yielded 0.22″ per pixel and a field close to 2 minutes of arc. Seeing was 0.8″ or better throughout the night, and was very well sampled by the pixel scale used. Exposure times were 600 sec for filters *V* and *R*, and 900 sec for *B*. Flatfields and standard star calibration frames were also secured

[1]Based on observations made with the Nordic Optical Telescope sited on the island of La Palma in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

TABLE 1. Optical photometry of the knots.

Knot	Area (Kpc^2)	V(mag)	$B-V$ (mag)	$V-R$ (mag)	Comment
A	32	14.94±0.05	0.4	0.7	Seyfert nucleus
B	6.5	18.30±0.05	1.5	0.8	Second nucleus
1	12.1	20.1±0.7		0.5	H II region
2	7.5	19.9±0.3	0.1	0.4	H II region
3	8.5	19.4±0.3	0.6	0.6	H II region
4	17.5	18.7±0.2	0.6	0.5	H II region
5	23.7	20.0±0.3	0.1	0.6	H II region
6	7.5	20.2±0.4		0.9	
7	3.8	20.8±0.7		0.6	H II region
8	9.5	18.2±0.1	0.8	0.9	Star

TABLE 2. Optical and infrared photometry of the knots[a]

Knot	Radius (arcsec)	V(mag)	$B-V$(mag)	$V-K$(mag)
A	2.2	14.94±0.05	0.4	3
B	2.2	17.03±0.05	1.5	2.4
1	3	20.1±0.7		3.5
2	3	18.9±0.3	0.3	3.4
3	3	18.6±0.3	0.2	3.3
4	3	18.3±0.2	0.3	3.1
5	3	20.0±0.3	0.2	4.5
6	3	18.9±0.4		2.8
7	3	19.6±0.7		3.5
8	3	18.2±0.1	0.5	3

[a]The optical data in this table correspond to a fixed aperture equal to that used for the IR data by Appleton & Marcum (1993).

that same night. The images were treated following standard procedures for flat-fielding and sky subtraction, as well as for correcting nonlinear effects present in the CCD chip. The flux calibration of the images was achieved through the observation of the standard star La93-317 (Landolt 1973, Landolt 1983). Unfortunately the CCD employed was cosmetically far from perfect producing frames with vertical stripes that are still noticeable in the reduced images.

3. THE DATA

Figures 1(a)–1(c) (Plate 77) show the images and contour plots for the B, V, and R frames respectively. Several knots of intense emission have been marked and labeled in the R contour plot [Fig. 1(c)]. We have followed the same notation used by AM to facilitate the comparison between the IR and optical knots. Table 1 gives magnitudes and colors for those regions marked in Fig. 1(c). In Table 1, column 1 identifies the knots, columns 2 gives V magnitudes, columns 3 and 4 show B-V and V-R colors, column 5 gives the area of the knots in kpc yielding the measured fluxes, and column 6 is reserved for comments. Regions 1, 6, and 7 are too faint in B for its B-V color to be calculated. The errors given in Table 1 are dominated by flux calibration errors in the case of both the Seyfert nucleus, knot A, and source B. For the fainter features the errors are dominated by sky noise.

The region marked as A in Fig. 1, corresponds to the Seyfert nucleus. Note that the colors given in Table 1 for this region differ noticeably from those given by de Vaucouleurs & de Vaucouleurs (1975) since these authors gave integrated colors for the entire galaxy, while here, the colors for the nucleus alone are given. Indeed our colors are bluer than those given by de Vaucouleurs & de Vaucouleurs (1975), as expected for a Seyfert nucleus.

Region B is an object 3.8″ NW of the Seyfert nucleus previously noticed in the light of the continuum at 6742 Å (RES), and in the IR work of AM. This object is now clearly resolved in the present data. Because region B is too close to the Seyfert nucleus, special care has to be taken to measure its colors from the optical images. Thus to obtain the colors given in Table 1 for object B a smooth background has been subtracted. This background, corresponding to the surface brightness of the Seyfert bulge, has been obtained by fitting a smooth polynomial to the brightness distribution of the Seyfert nucleus and surrounding nebulosity in a region not affected either by object B or by the ring. The selected region corresponds roughly to azimuthal angle 90°. For the rest of the regions in Table 1 this correction has not been applied, as these regions are far enough from the Seyfert nucleus that there is not any appreciable background contamination due to either the strong Seyfert nucleus or its bulge. For regions 1 to 7 the colors have been obtained by adding the fluxes of all the pixels within an area enclosing the given region. All these knots show colors similar to those of late type stellar populations. Knots 1, 6, and 7 are not detected in B and barely detected in V. The colors given have not been corrected for extinction internal to the galaxy itself, so all the intrinsic colors should be much bluer than they appear as the ring of NGC 985 is known to have patchy extinction averaging at least $A_v=4$ mag (RES). This, and the fact that all these regions show strong Hα emission, lead RES to the conclusion that they are Giant H II regions, most likely containing clusters of young stars. Region 8 is very likely a field star of type K (Johnson 1966) laying just on the outer side of the north edge of the ring of NGC 985.

Figure 2 shows a color-color diagram for all the knots for which both optical data from this work and near-IR data from AM exist. All knots have very red V-K colors and some of them, namely knots 1 and 6, are indeed more conspicuous in the IR than they are in the optical. Table 2 shows the data plotted. Notice that the optical colors in Table 2 differ from those given in Table 1 due to the use of a different aperture when computing the optical fluxes shown in Table 2. This has been done in order to compare with the IR colors of AM which were obtained from their IR images with a fixed aperture of radius 3 arcseconds centered on each knot. This aperture is in all instances larger than the area actually occupied by the individual knots, reason why all knots show brighter magnitudes with the larger aperture.

We have also plotted in Fig. 2 the evolutionary tracks of Charlot and Bruzual (1991) as adapted by Appleton *et al.* (1992). Figure 2 shows that all the knots lie very close in age, indicating a common triggering mechanism for the onset of star formation in all these knots, confirming the suggestion made by RES that a plausible origin for the burst of star formation was the interaction with another galaxy. From Fig. 2 it is possible to estimate the age of the burst of star formation occurring in NGC 985. Following the evolutionary tracks of Charlot & Bruzual (1991) the age of the burst

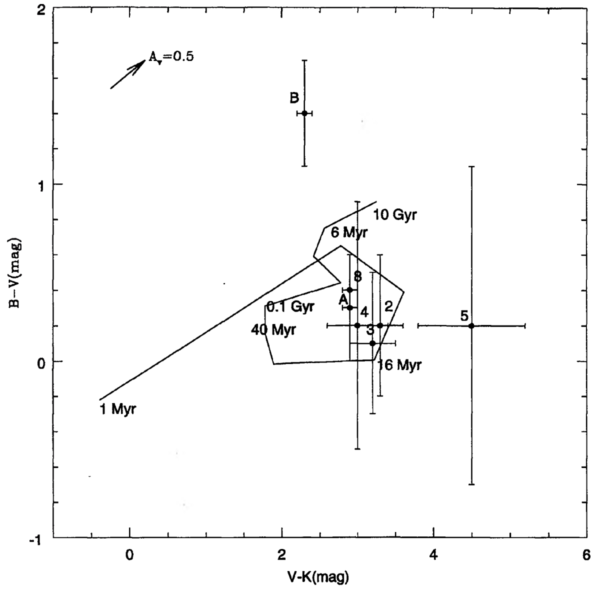

FIG. 2. Optical-IR color-color diagram for the knots of emission in NGC 985. The optical data are from this work. The IR data are from Appleton & Marcum (1993) (see Table 2). The evolutionary tracks are from Charlot & Bruzual (1991). The ages given in numbers represent the time since the onset of the burst of star formation.

should be less than about 40 Myr, if one allows for about 1 mag of extinction, as calculated by RES for region 4. Notice that this estimation of the age of the burst of star formation can be of great help for people modeling this system.

4. THE DOUBLE NUCLEUS OF NGC 985

The contour map of the central region of NGC 985 (Fig. 3) shows two clearly differentiated peaks of emission marked A and B in Fig. 1(c), having very different optical colors (Table 1). The colors of region B are very red, proper of type

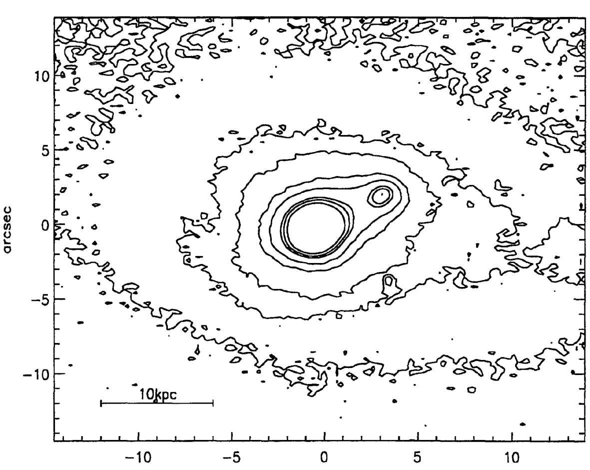

FIG. 3. R band contour map of the nuclear region of NGC 985. North is at the top and east is at the left. The dynamic range plotted is 0.02 (3σ) to 0.77 adu/sec/ arcsec^2 that corresponds to the peak of the emission from region B.

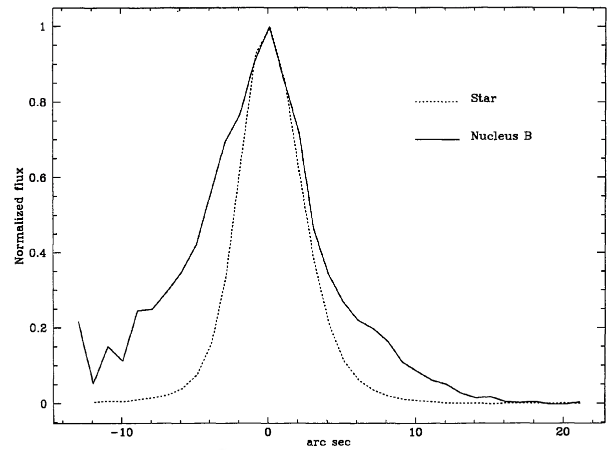

FIG. 4. Brightness profiles of source B and a field star. Both profiles are normalized to unity. The contribution of the bulb of the Seyfert galaxy plus adjacent nebulosity has been subtracted from the profile of source B as explained in the text. Note how B is not point like.

M stars or redder. In particular, the B-V = 1.5 color of source B is much redder than any of the other knots identified in this galaxy, including the Seyfert nucleus. This very red color can only be interpreted as arising from a stellar population fully devoided of young stars, together with a sizeable amount of extinction.

In order to test whether object B is a old field star in the line of sight we have compared its brightness profile with that of one of the field stars in the CCD frame obtained under the same seeing conditions. Figure 4 shows both profiles normalized to the same peak intensity. The contribution of the bulge of the Seyfert galaxy has been subtracted from the profile of object B as explained before. The resulting profile, plotted in Figure 4, together with the star profile shows clearly that object B is resolved, i.e., not point like as the field star. Note that in Fig. 4 the profile of the nuclear source has been truncated toward the left side due to the proximity of the Seyfert nucleus. Moreover, a fit of the brightness distribution of object B to a $r^{1/4}$ de Vaucouleurs brightness distribution (Fig. 5) produces acceptable results. This, added to the red colors and the fact that object B does not emit in Hα (RES) lead us to conclude that object B is a spheroid, very likely the bulge of a spiral or an elliptical galaxy. Recent radio observations made at the VLA by Appleton & Ghigo (personal communication) also support the claim that object B is resolved. In the observations by Appleton and Ghigo, the nucleus of NGC 985 is resolved into a double source at 2.3 cm wavelength. The second source lies exactly on top of knot B.

A further property of object B that can be extracted from the photometry of our B frame is its absolute B magnitude. Its apparent magnitude has been obtained through aperture photometry of region B allowing for a background subtraction that takes care of the contribution of the Seyfert bulge. Taking an H_0 value of 75 kms^{-1} Mpc^{-1}, the distance to NGC 985 is d=231 Mpc, yielding an absolute magnitude for region B of M_B=−16.6 or brighter if one takes into account the object B must be seen through a sizeable amount of ex-

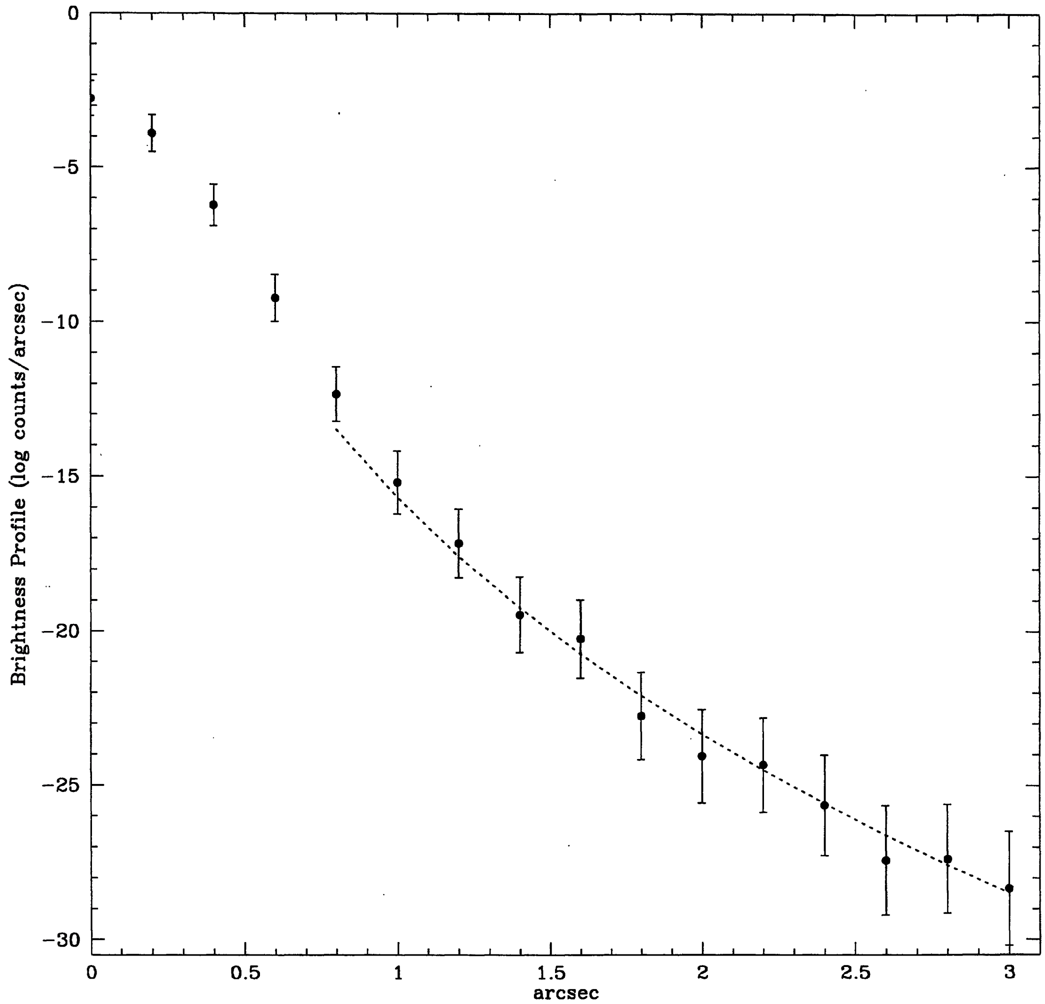

FIG. 5. Fit to the brightness profile of object B with a brightness distribution of the form $\log(I)=a+br^{1/4}$. We obtain $a=0.99$ and $b=-1.08$ with a correlation coefficient of 0.99. Note that the brightness profile correspond to a linear scan through source B.

tinction. This value is therefore within the range of values expected for spiral bulges or dwarf elliptical galaxies (Kormendy 1987).

We thus conclude that NGC 985 is a composite system having two nuclei, namely the Seyfert nucleus and a spheroidal bulge or elliptical galaxy, which corresponds to object B in our figures.

5. A SCENARIO FOR NGC 985

The finding of this second nucleus (knot B) lends support to the models of Lynds and Toomre (1976), who proposed that in the subclass of ring galaxies called RE by Theys & Spiegel (1976), an off center collision would displace the nucleus off the galaxy's disk plane and, depending on the viewing angle, would produce an apparently empty ring due to the disk's nucleus looking like burried in the ring. That could perhaps be the case for NGC 985, where, were it not for the onset of Seyfert activity in the original disk nucleus, it would have gone unnoticed amongst the many bright knots seen in the ring.

Furthermore, a qualitative explanation of the morphology of NGC 985 follows from the recent models and numerical simulations of Gerber *et al.* (1992). A plausible scenario for NGC 985 would start with the collision off the original disk galaxy of either an elliptical or a spheroidal galaxy. The intruder galaxy would impinge almost normally to the plane of the disk galaxy with a relatively small impact parameter. According to the models of Gerber *et al.* (1992) the approach of the intruder galaxy would lift the disk's nucleus off the disk's plane, inducing at the same time some funneling of matter (gas and stars) toward the impact point, thus producing a density enhancement that could be responsible for the onset of nuclear activity in the disk galaxy's nucleus.

The formation of the ring would follow along the lines described by these authors for the Arp 147 system (Gerber *et al.* 1992), i.e., part of the material that was funneled towards the inner region of the disk galaxy recedes from the impact point soon after closer approach, meeting on its way out material that is still falling in. This process results into an expanding arc of high density shocked material. This expanding arc could act as the triggering mechanism for star formation episodes along the disk now converted into a ring. This would also explain the quasi simultaneity of the onset of star formation in all the knots found in the ring.

The fact that NGC 985 shows only a partial ring extending mostly west and north can probably be explained by the actual geometry of the galaxy encounter, perhaps allowing for a larger impact parameter between the two colliding galaxies, although a quantitative explanation will have to come from the application of the actual models to this object.

A different scenario has been proposed by AM to explain the morphology of NGC 985. These authors realized that after subtracting an $r^{1/4}$ nuclear bulge, belonging to the Seyfert host, object B appeared at one of the ends of a linear feature pointing away from it. This object B plus the linear feature and its faintish bent continuation toward the north are then interpreted as an IR bar plus a tightly wrapped one arm spiral, which these authors interpret as the result of a two galaxy collision in which the original galaxy would be what now is source B with its original disk, while the current Seyfert nucleus would have been an earlier dwarf elliptical that would have struck the former disk galaxy (see AM for more details).

Although both scenarios are plausible, detailed morphological as well as kinematical models of NGC 985 (out of the scope of this paper and of the range of expertise of the authors) are required before a definitive explanation of the interaction of the two nuclei observed in this system is found.

6. CONCLUSIONS

We have presented subarcsecond broad band images of the Seyfert ring galaxy NGC 985, showing clear cut evidence of the presence of a second nuclear bulge located 3.8″ NW of the active nucleus. The optical colors of this second bulge and its brightness profile, resolved when compared to a start-like profile, lead us to conclude that this object is indeed a spheroidal system with an absolute magnitude of at least $M_B=-16.6$. This spheroidal system could be the intruder galaxy that gave rise to the tidal disruption of the original disk galaxy and later to the production of the ring of star formation. There are nonetheless alternative explanations. An important result is the fact that all knots whose B flux could be measured reliably are coeval, implying a unique triggering mechanism for the onset of star formation throughout the ring.

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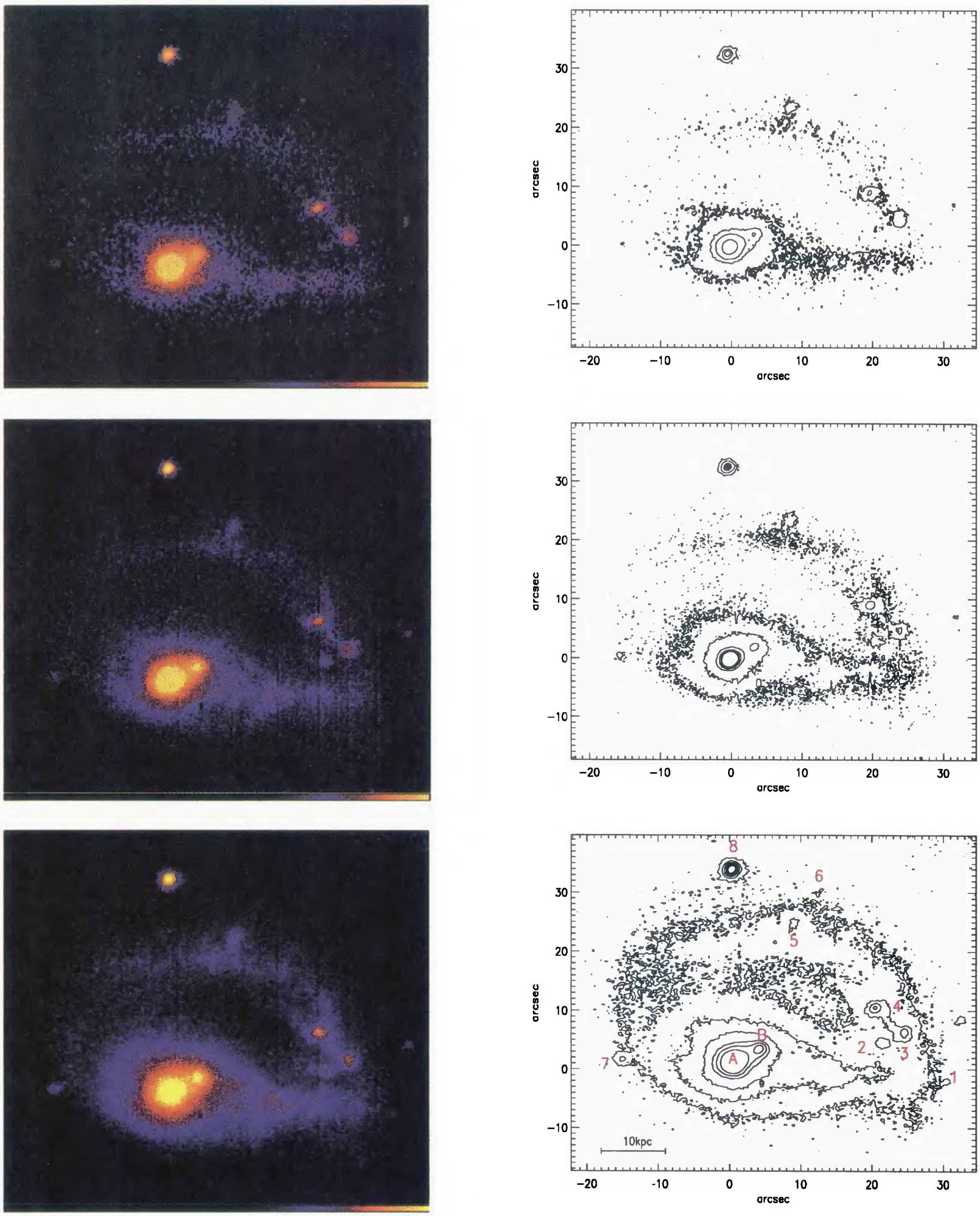

FIG. 1. (a)–(c) *B*, *V*, and *R* images and contour plots of NGC 985. North is at the top and east at the left. Several knots of emission are marked on the *R* contour plot. For the contours the lowest level corresponds to the 3σ value, the step size between contours is also 3σ.

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