Astron. Astrophys. 319, 430–434 (1997)

ASTRONOMY
AND
ASTROPHYSICS

IC 1689: S0 galaxy with inner polar disk

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Received 29 April 1996 / Accepted 22 July 1996

Abstract. The results of spectroscopic observations of the S0 galaxy IC 1689 are given. The radial velocity curves constructed from the measurements of Hα and [NII]λ6583 lines show that in the galaxy interior there is a gas disk (r$\approx$3 kpc) rotating around the axis placed in the main plane of the galaxy (polar disk). Active star formation occurs in the outer part of the disk (in the ring). Both Hα and [NII]λ6583 emission lines are observed here. Only collisionally excited [NII] radiates in the inner regions of the disk.

Key words: galaxies: IC 1689; kinematics and dynamics; interactions; peculiar; spectroscopy

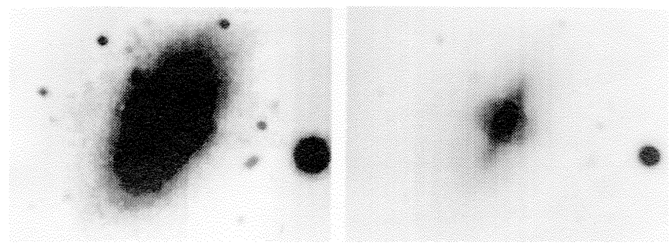

Fig. 1. B-band image of IC 1689 displayed at two different contrasts (in a logarithmic gray scale). North is at the top and east to the left. The entire image field is 60 $\times$ 80arcsec^2.

1. Introduction

S0 galaxy IC 1689 was included in the "Catalog of polar-ring galaxies, candidates and related objects" of Whitmore et al. (1990) (hereafter PRC) as a "good candidate" to polar-ring galaxies (PRGs). The polar ring is best seen in U band (see the reproduction in van Gorkom et al.,1987) on underexposed pictures because in contrast to "classic" PRGs it is an *inner* polar ring. This fact is well demonstrated in Fig.1 taken from our paper (Reshetnikov et al.,1995) (hereafter RHY) devoted to a detailed photometric study of the galaxy. [1] The ring is nearly face-on but nevertheless has elliptical form with the major axis nearly perpendicular to the major axis of the galaxy.

The main results obtained in RHY are as follows: the ring structure is bluer than other regions of the galaxy; it is projected on the main body of the galaxy to the south of its minor axis and contains some dust which introduces absorption and reddening; to the north of the minor axis the ring is seen through the galaxy which is practically transparent. On the basis of the absorption distribution along the major axis of the galaxy south of the center, the ring could actually be the most dense and brightest part of a more extended structure maybe a disk. The observed ring brightness and colours could be ascribed to an ongoing burst of star formation in it.

To confirm these conclusions and check the suppositions we performed spectral observations of IC 1689. In this paper we give the results of such observations and general discussion on the nature of the above subsystem.

2. Observations and reductions

The observations were made on October 14, 1995 at the prime focus of the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences with long-slit spectrograph UAGS. Slit of 2"$\times$210" and CCD detector with 530x580 pixels each 18x24 μm^2 were used. Scale along the slit was 0.4"/pixel, dispersion - 1.55Å/pixel. Four frames with exposure time of 30 min each were obtained: two with slit position angle of 164^o (along the major axis of the galaxy) and two with that of 74^o (along the major axis of ring structure). Spectra of Ar-Ne-He comparison lines were obtained before and after each galaxy exposition in order to calibrate accurately the wavelength scale. During the observations seeing was about 1.5". All spectra were obtained in red spectral region (6200 - 7100 Å). Log of observations is given in Table 1.

The reductions were carried out by standard method using the ESO-MIDAS package LONG (MIDAS User guide 1994). These included bias subtraction, flat-field corrections, wavelength calibration and sky subtraction.

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[1] Because of mistake in printing the orientation of Fig.1 in RHY is erroneous (actually north is at the bottom)

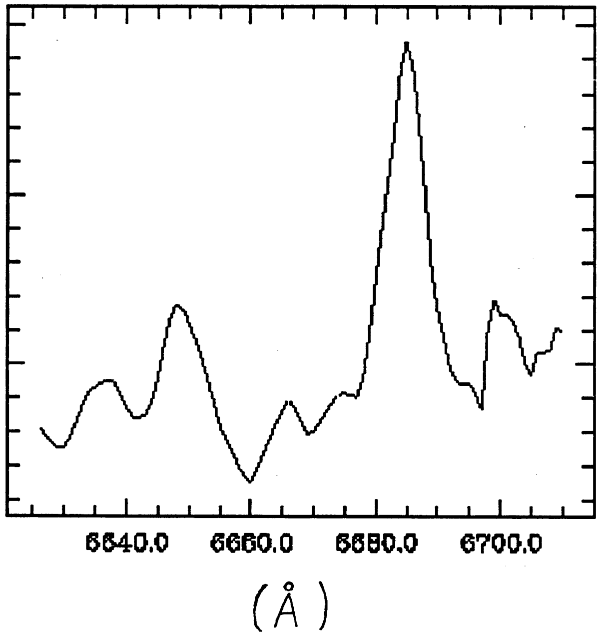

Fig. 2. Nuclear Hα spectrum of IC 1689 (vertical scale is arbitrary intensity unit).

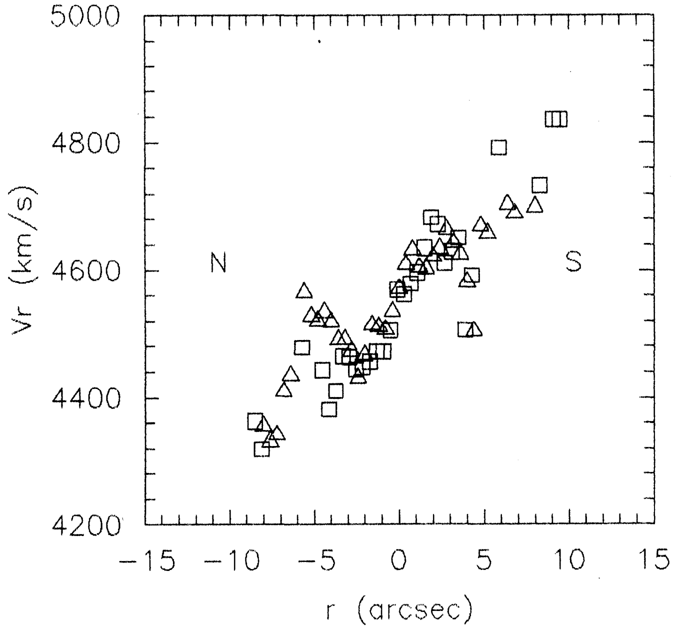

Fig. 3. Absorption-line rotation curve of IC 1689. Different symbols represent heliocentric radial velocities obtained from different spectra.

Table 1. Observations

Date	Spectra	Exp. (min.)	Slit P.A.	Seeing
14.10.1995	U02712	30^m	164^o	1.5"
	U02713	30	164	1.5
	U02717	30	74	1.5
	U02718	30	74	1.5

3. Results

3.1. Emission spectrum of the galaxy nucleus

In all four spectra of IC 1689 the emission lines [NII]λ6548,6583 and [SII]λ6717,6731 are well notable in the galaxy nucleus (its position was determined by maximum intensity in continuum). For the very central region of 1.6" in diameter the equivalent width of [NII]λ6583 is 1.9$\pm$0.2 Å, FWHM (after correction for instrumental width) is 250$\pm$50 km/s. Hα emission is seen above the appreciable absorption (see Fig.2). Even after correction for Balmer absorption the intensity ratio Hα/[NII]λ6583 remains $\leq$1. By all these characteristics IC 1689 may be related to LINERs.

According to van Gorkom et al.(1987) the systematic velocity of IC 1689 is 4567 km/s. Our spectra allow to verify this value. To make this we use the emission line [NII]λ6583 which is the most conspicuous in nuclear spectrum. The mean value of heliocentric radial velocity obtained using all four spectra proved to be V_{hel} = 4566$\pm$17 km/s in excellent agreement with the value of van Gorkom et al. (the final error is determined not by the scatter of individual values but by uncertainty of zero-point of velocity scale which is found to be 15 km/s from the measurements of night-sky lines).

3.2. Absorption spectrum along the major axis of the galaxy

Two spectra along the major axis of the galaxy are exposed enough to see absorption line λ6495 (the blend of CaI + FeI). The results of the measurements of this line (under assumption on gaussian profile) are shown in Fig.3. In spite of considerable scatter one can find for the stellar component the rotation velocity of 230 km/s ($\pm$20 km/s) at the distance of 8.7" ($\pm$0.25") from the nucleus.

Using H_o = 75 km/s/Mpc and radial velocity V_r = 4567 km/s (absorption line gives the same value) we obtain the crude (assuming spherical mass distribution) estimate of the mass m($\leq$8.7") = $3.3 \times 10^{10} m_\odot$. Our photometry (RHY) gives the luminosity $L_B(\leq 8.7") = 3.2 \times 10^9 L_\odot$. Therefore for the m/L_B ratio we obtain $m/L_B \approx 10$.

Though the galaxy is seen nearly edge-on the small correction for the inclination must be done as well as the correction for integration along the line of sight. Both corrections increase the rotation velocity. Hence, m = $3.3 \times 10^{10} m_\odot$ is the lower limit and actually $m/L_B \geq 10$.

3.3. Emission spectrum along the major axis of the inner elliptical structure

The isophotal map of the spectrum in the Hα + [NII] region obtained along the major axis of the inner elliptical structure is reproduced in Fig.4 (the sum of two original spectra). It is well seen that both lines demonstrate appreciable tilt pointing

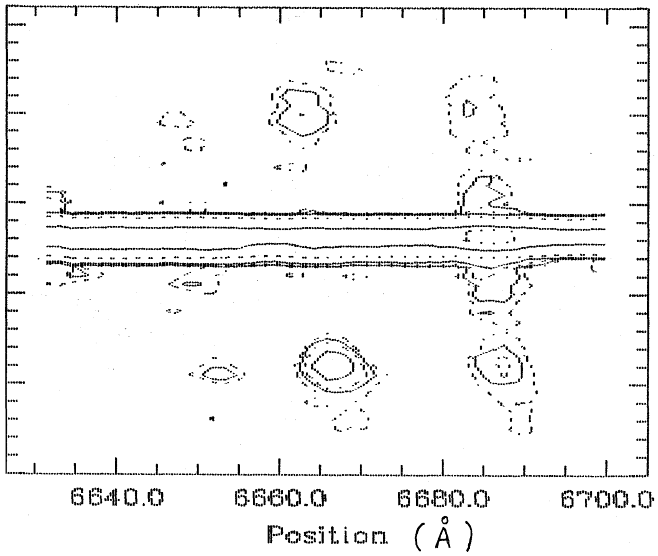

Fig. 4. Spatial structure of Hα and [NII] emission lines at slit along the major axis of the ring (continuum influence is suppressed by numerical treatment).

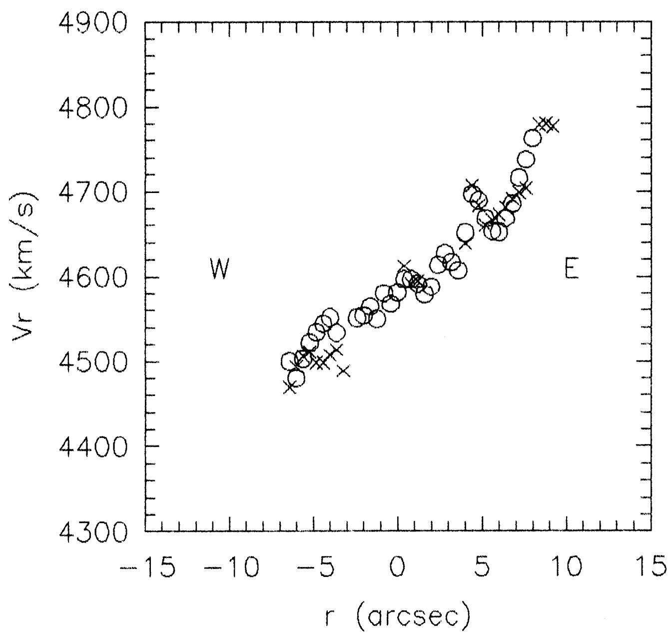

Fig. 5. Emission-line rotation curve of IC 1689 at slit along the major axis of the ring (crosses - Hα, circles - [NII]λ6583).

to rotation of the emitting gas in the plane perpendicular to the main plane of the galaxy.

The rotation curve from the measurements of Hα and [NII]λ6583 lines is given in Fig.5. Evidently both lines give the same rotation curve showing that they originate in the gas belonging to the same subsystem. At the distance of 8.7" (we choose this value because it is the same as for absorption spectrum) the radial velocity is about 160 km/s. Adopting that the true form of the elliptical structure is circular one can find by apparent ellipticity of b/a = 0.8 (see Fig.1) that the rotation velocity at this distance (after taking into account the inclination) is about 270 km/s.

With this value we obtain m/L_B=14. It is neccessary to point out that this value is the upper limit of the ratio because the true form may be elliptical, with the major axis of ellipse belonging to the principal plane of the galaxy. In this case the reduction for inclination will be smaller and m/L_B ratio decreases. The observed radial velocity (160 km/s) is the lower limit of rotation velocity for which we have m/L_B=5. But this value is smaller than that obtained in item 3.2. Therefore we may adopt that $10 \leq m/L_B \leq 14$. This interval is usual for S0 galaxies.

The second fact deserving attention in Fig.4 is a different structure of emission lines Hα and [NII]λ6583. The Hα emission is concentrated in two regions symmetrical relative to the nucleus and placed at the distances $\geq$4" from it. Probably this is a counterpart of the ring observed in optical continuum and UV.

To the contrary [NII]λ6583 emission is well seen also in the central part of the galaxy where there are neither additional continuum emission (above the galaxy contribution), nor the Hα emission. The isophote structure of λ6583 line confirms the supposition put forward in RHY that in IC 1689 a gaseous disk (not only a ring) does exist. Such a disk rotates in a plane perpendicular to the principal plane of the galaxy. Taking into account the similarity of kinematic characteristics of gas emitting in Hα and[NII] one can conclude that the visible ring is simply the outer brightest part of the disk.

3.4. Emission spectrum along the major axis of the galaxy

The isophotal map of the spectrum obtained along the major axis of the galaxy (or along the minor axis of elliptical structure) is shown in Fig.6. This spectrum is also the sum of two original spectra obtained in Hα + [NII] region.

Unlike Fig.5 here the line [NII]λ6583 demonstrates no tilt (at least up to distance of 9" from the nucleus), while a small tilt may be seen in Hα. As in Fig.5 the [NII] line is well seen in all positions within 9" from the nucleus while Hα emission is not seen in central region. But there are weak extensions of emission at large distances from the nucleus and these extensions evidently demonstrate the tilt.

The results of the measurements are given in Fig.7. The intricate character of the radial velocity curve may be explained if one supposes the existence of two subsystems of emitting gas: the first subsystem related to the polar disk and the second one connected with main galaxy. Within 8" from the center the first subsystem dominates. Because of geometry the radial velocity of the gas belonging to this subsystem must be near zero. In fact, radial velocities of [NII]λ6583 line demonstrate such a picture. Subsystem connected with main galaxy does not contribute to [NII] emission in this region. Its influence may be seen only for r$\geq$ 8" at the southern part of the galaxy.

As for Hα emission, the existence of the second subsystem is well seen at r $\geq$ 6". Though the Hα component of this subsystem is evidently much more weak than that of disk subsystem,

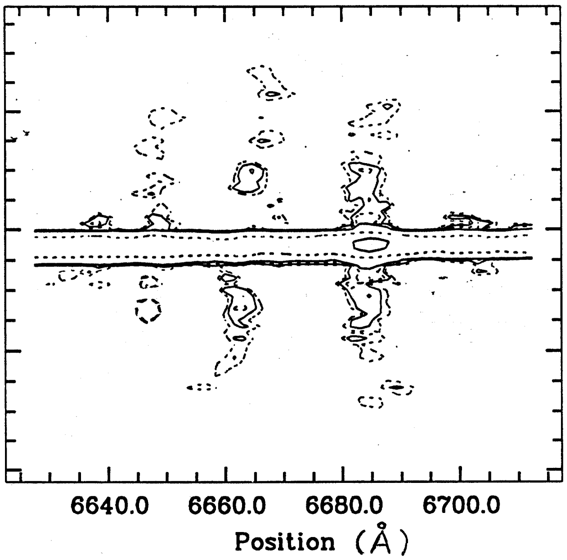

Fig. 6. Spatial structure of Hα and [NII] emission lines at slit along the major axis of IC 1689 (continuum influence is suppressed by numerical treatment)

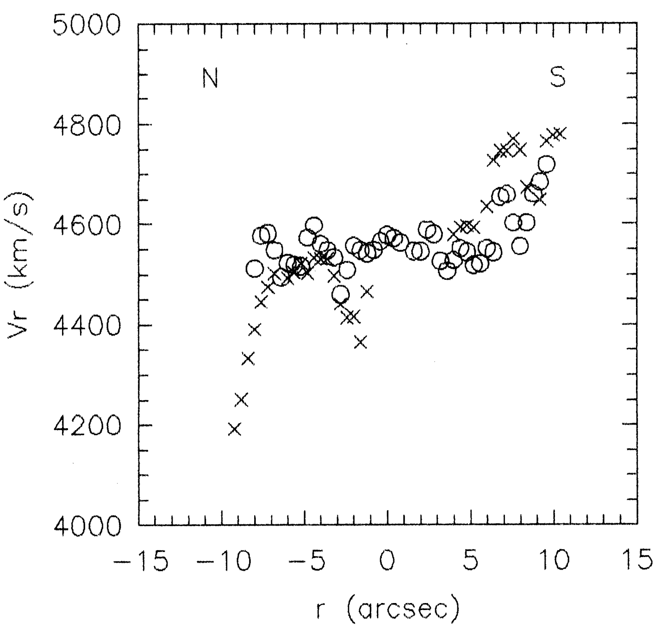

Fig. 7. Emission-line rotation curve at slit along the major axis of IC 1689 (crosses - Hα, circles - [NII]λ6583).

its influence is conspicuous even in the region at r $\leq$ 6". It provokes the shift of line center because its radial velocity differs from zero. This explains systematic difference between radial velocities found from [NII]λ6583 and Hα lines in this region.

If one excludes points belonging to disk subsystem, the Hα rotation curve will be nearly the same as that found using absorption spectrum (see Fig.3). This confirms the explanation of radial velocity curve given above.

4. Discussion

The results of this work and RHY show that by its integral photometric and spectral characteristics IC 1689 is a normal S0-galaxy with $m/L_B \approx 10 - 15$. But in the plane near perpendicular to the principal plane of the galaxy there is a gas disk (with radius $\leq$3 kpc and mass m(HI)$\approx 10^8$ $m_\odot$ according to RHY) which rotates around the axis placed near the principal galaxy plane. By this peculiarity the galaxy is an object related to PRGs, though polar disk is of small dimension and located in the galaxy interior. Such galaxies may be related also to S0 galaxies with strong kinematical decoupling of the gaseous and stellar components studied by Bertola et al. (1992).

It is usually accepted that the appearance in the galaxy of the gas subsystem rotating in the plane perpendicular to its principal plane is a consequence of interaction between galaxies accompanied by accretion of the matter from gas rich companion or its merging (Whitmore et al. 1990). In the case of IC 1689 such an event is very probable because the galaxy is a member of group of galaxies (Burns et al. 1987, Garcia 1993) and there are some evidences of recent interaction such as large-scale bending of stellar disk (by 11° according to RHY) and possible existence of kinematically decoupled stellar nucleus within r $= \pm 5$" (see Fig.3). In addition, as it was noted in RHY, there are two diffuse objects close to the minor axis of the galaxy which may be the remnants of galaxies participating in interaction.

The modeling of interactions shows (e.g. Weil & Hernquist, 1993) that when moving gas rich galaxy close to the massive one the former loses gas component which forms a ring around the latter. The ring radius depends on the mass concentration to the nucleus in the massive galaxy and either outer or inner ring may be formed (Sotnikova 1996). (According to Bertola et al. (1992) the acquisition events in S0 galaxies are a widespread phenomenon and in 40% of these galaxies the ionized gas is of external origin.) Having in mind this scenario the results of our observations may be interpreted as follows.

As a result of interaction sufficiently dense gas ring has been formed in the near-polar plane of IC 1689. For some reasons the burst of star formation has occured in the ring. Both photometric (extra brightness, blue colours, existence of reddening by dust) and spectroscopic (strong Hα emission found in this work) data point to this fact.

Let us verify the possibility of star formation in the ring. According to Kennicutt (1989) for the thin gaseous disks of normal galaxies there is a threshold surface density of gas ($1 - 10\ m_\odot/pc^2$) over which gravitational instability and a consequent burst of star formation occur. Assuming a mass of HI in the range $1 - 5.6 \times 10^8 m_\odot$ (RHY, van Gorkom et al.1987, Giovanelli & Haynes 1989) and taking into account the observed ring dimensions one can obtain $4.5 - 25\ m_\odot/pc^2$ for mean surface density of the gas in the ring. Hence, the gravitational instability in the region where the space density is so high that the threshold surface density has been exceeded may be considered as a possible reason of starforming activity. The increasing of space density of the gas may be due to large-scale compression of the ring when it approaches the preferable (polar) plane in the

Table 2. Ring of IC 1689

Characteristic	E-part	W-part
$< \mu_B >$	23.2	23.6
W(Hα) (Å)	10.3	4.5
W([NII]) (Å)	3.3	3
I(Hα)/I([NII]λ6583)	3.0	1.5

course of evolution (Christodoulou & Tohline 1993). The interaction of the ring gas with gas component of the main galaxy may be one more reason of starforming activity.

It should be noted that the intensity of star formation differs along the ring. In fact, as one can see from Table 2, in the eastern part of the ring both Hα emission and additional continuum emission (RHY) are stronger.

Due to low density of galactic interstellar matter (it should be recalled that the galaxy is nearly transparent (RHY) and give very weak gaseous emission) the ring is not strongly disturbed by interaction with diffuse galactic matter but nevertheless some of the ring gas loses its velocity and begins to fall down to the nucleus forming gas disk. Because of low density in the inner parts of the disk there is no star formation here. Therefore in this region there are no young hot stars whose radiation might ionize hydrogen providing Hα emission. Only collisionally excited [NII] gives emission here. Shocks arising from the motion of polar disk gas in an oval potential of the galaxy (Wakamatsu 1993) may be the source of gas ionization and excitation.

The weak accretion of the disk gas onto the nucleus is probably responsible for its LINER characteristics.

5. Conclusions

a) We present the results of spectral observations of IC 1689 carried out at the 6-m telescope with two slit positions. Both spectra show strong emission lines of Hα and [NII] in the polar ring.

b) Though the spatial distribution of Hα and [NII]λ6583 emission lines is different, the observed velocity curves show that both lines originate in the same gas subsystem likely a polar disk. Differences in line distribution are presumably due to differences in physical conditions along the disk radius: while in the external regions the emission can be ascribed mainly to photoionization, the collisional excitation could dominate in the inner regions.

c) In the outer region of the disk (in the ring) the active star formation occurs as seen from blue colours, additional continuum brightness (above the galaxy contribution) and strong Hα emission.

d) The formation of gaseous disk from the polar ring originally formed as a result of matter accretion by galaxy interaction may be due to braking the gas of the ring by weak interaction with low-density gas component of the galaxy.

e) The galaxy is an ordinary S0 whose nucleus shows LINER-like spectroscopic properties.

Acknowledgements. We are grateful to 6-m telescope Committee for the allocation of observing time, to executive observer at 6-m telescope A.N.Burenkov and to O.K.Sil'chenko for her assistance during the observations; the discussion of the results with Drs. N.Ya. Sotnikova and E.V. Volkov is kindly acknowledged. Our thanks to referee (Dr. L.M.Buson) for useful comments. The work was supported by grants N 94-2-06026-a and 95-02-05596 from Russian Foundation for Basic Research and grant A-03-013 from ESO C&EE Programme.

References

Bertola F., Buson L.M., Zeilinger W.W. 1992, ApJ 401, L79
Burns J.O., Hanish R.J., White R.A. et al. 1987, AJ 94, 587
Christodoulou D.M., Tohline J.E. 1993, ApJ 403, 110
Garsia A.M. 1993, A&AS 100, 47
Giovanelli R., Haynes M.P. 1989, AJ 97, 633
Kennicutt R.C. 1989, ApJ 344, 685
Reshetnikov V.P., Hagen-Thorn V.A., Yakovleva V.A. 1995, A&A 303, 398 (RHY)
Sotnikova N.Ya. 1996, Afz 39, 259 (in Russian)
van Gorkom J.H., Schechter P.L., Kristian J. 1987, ApJ 314, 457
Wakamatsu K. 1993, AJ 105, 1745
Weil M.L., Hernquist L. 1993, ApJ 405, 142
Whitmore B.C., Lucas R.A., McElroy D.B. et al. 1990, AJ 100, 1489 (PRC)

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