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Candidate polar-ring galaxies in the Hubble Deep Field

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Abstract. We discuss the properties of two peculiar galaxies (2-809 and 2-906) selected in the Hubble Deep Field as possible candidates to high-redshift ($z \approx 1$) polar-ring galaxies. We found that the presence of polar-ring galaxies in a random deep field gives some support for a galaxy interaction rate steeply increasing with redshift.

Key words: galaxies: interaction, photometry, peculiar, structure

1. Introduction

Polar-ring galaxies (PRGs) are among the most unusual and rare extragalactic objects. PRGs are early-type galaxies with a large-scale ring of gas, dust and stars orbiting nearly perpendicular to the major axis of the host galaxy. According to Whitmore et al. (1990) (PRC) about 0.5% of all nearby S0 galaxies are observed with a polar ring. After correction for various selection effects, the fraction increases to about 5% of S0 galaxies which have, or have had a polar ring.

An existence of two almost orthogonal kinematic systems strongly suggests that PRGs are formed in galactic interactions. The two most straightforward mechanisms of the polar-ring formation - the accretion of matter from a nearby gas rich galaxy and the capture and merging of a companion - were recently illustrated by means of numerical simulations (Weil & Hernquist 1993, Sotnikova 1996, Reshetnikov & Sotnikova 1997). Besides, there are several binary systems in the local universe clearly demonstrating polar-rings formation in galactic interactions (e.g., Reshetnikov et al. 1996).

It is usually believed that galaxy interactions were more frequent in the past (e.g., Keel 1996 for a recent review). Therefore, one can expect to find a larger fraction of PRGs among high-redshift objects (assuming that the lifetime of polar rings is limited). Comparison of the PRGs fraction in the local universe with that among high-redshift galaxies will provide an estimate of the rate of this specific type of interactions (leading to polar-ring formation) as a function of redshift. Note that recent statistics of distant $ring$ galaxies provided strong evidence for a very steep increase of a galaxy interaction rate with redshift (Lavery et al. 1996).

The Hubble Deep Field (HDF) (Williams et al. 1996) images, obtained with the Hubble Space Telescope during December 1995, permit to study distant galaxies in unprecedented details. In this note we present two polar-ring candidates found in the HDF and discuss possible consequences of the PRGs presence in the HDF for the evolution of interaction rate.

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Table 1. General characteristics of the galaxies

ID	α(m:s)	$\delta(':'')$	z	v_t	$u-b$	$b-v$	$v-i$
2-809	36:52.88	14:05.1	0.64	24.05	0.53	0.78	0.79
2-906	36:56.13	13:29.7		24.00	0.54	0.23	0.56

2. PRGs in the Hubble Deep Field

After visual inspection of high resolution (3069 × 3100 pixels) colour images of the HDF stored on the ST ScI world-wide web site, we selected two relatively bright galaxies - 2-809 and 2-906 - as the most promising candidates in high-redshift PRGs. The galaxies do not have measured spectroscopic redshifts.

The global photometric characteristics of the galaxies according to Williams et al. (1996) are summarized in the Table 1. The columns of the table are: galaxy identification; coordinates (epoch J2000); photometric redshift (Lanzetta et al. 1996); "total" magnitude[1] in the F606W filter (v magnitude); isophotal colours (F300W−F450W as $u-b$, F450W−F606W as $b-v$, and F606W−F814W as $v-i$) measured to a faint limiting isophote determined from the summed F606W+F814W image.

In order to study polar-ring candidates, we retrieved and processed the HDF images (produced by the Version 2 drizzle algorithm) of the galaxies in the MIDAS environment.

2.1. 2-809

In Fig. 1 we present a reproduction of the galaxy from the combined F606W+F814W frame (left side of the figure). Right side

[1] All magnitudes in the paper are in the AB system (Oke 1974): $m_{AB} = -2.5\log f_\nu - 48.60$, where f_ν is the flux density in units of erg s^{-1} cm^{-2} Hz^{-1}

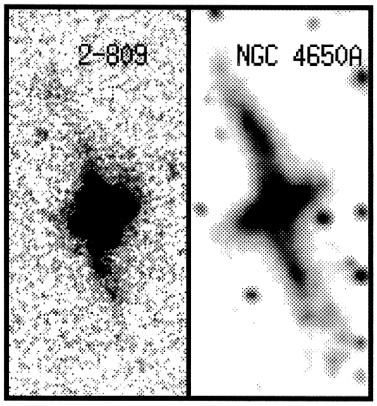

Fig. 1. Deep (F606W+F814W) image of 2-809 (left). The size of the image is $3''\times6.6''$. Right – Digital Sky Survey image of NGC 4650A ($2'\times4.7'$.) Both images are in arbitrary orientation.

of the figure shows DSS[2] image of the optical counterpart of 2-809 among local PRGs (NGC 4650A). As one can see, 2-809 resembles remarkably the well-known polar-ring galaxy NGC 4650A.

Fig. 2 shows isophotal contour map of 2-809 constructed from the summed F606W+F814W frame. Two warped extended structures are stretched along the minor axis of the galaxy out to at least r =2″. The morphological similarity between the galaxy and the classic PRGs (see, for instance, PRC) is evident in this figure. The east side of the suspected edge-on ring is extended towards peculiar galaxy 2-856. The projected distance between 2-809 and 2-856 is 4.4″or 26 (23) kpc for H_0 = 75 km/c/Mpc, z =0.64 and q_0 =0.05 (0.5). There is a small extention from NW side of 2-856 directed to 2-809. This feature may be interpreted as a consequence of tidal interaction between 2-856 and 2-809. Therefore, 2-856 may be considered as a possible "donor" galaxy - the stripped matter from this galaxy could form the ring around 2-809.

Fig. 3 presents the v and i photometric cuts along the major axis (P.A. = 174°) of the main body of 2-809 and along the bright inner part of the suspected ring (P.A. = 81°). The main body demonstrates peculiar surface brightness distribution. In the i passband the galaxy shows almost constant surface brightness within 0.3″ from the nucleus with the following fast decreasing of the brightness. In the v filter there is a minimum in the center of the galaxy resulted in local reddening in this region. Then, the $v-i$ colour systematically increases to the galactic periphery. On the contrary, the $b-v$ colour shows sharp minimum in the center (up to ≈+0.6) with the following increasing to 1-1.5. One can propose that we observe here the projection of the blue ring on the central region of the galaxy. The suspected ring is notably bluer in comparison with central galaxy (Fig. 3b).

The main observational characteristics of the galaxy are summarized in the Table 2 for q_0 =0.05 (0.5) and H_0 =75 km/s/Mpc. The total magnitudes and colours in the table were determined from the multi-aperture photometry. The results of our photometry are in good agreement with that of Williams et al. (1996). The observed characterstics of the central galaxy in the table are corrected for the ring contribution. The central galaxy demonstrates relatively red colours while the suspected ring is significantly bluer in the $b-v$ colour. The difference in observed colours between the central galaxy and the ring is typical for local PRGs (e.g., Reshetnikov et al. 1994).

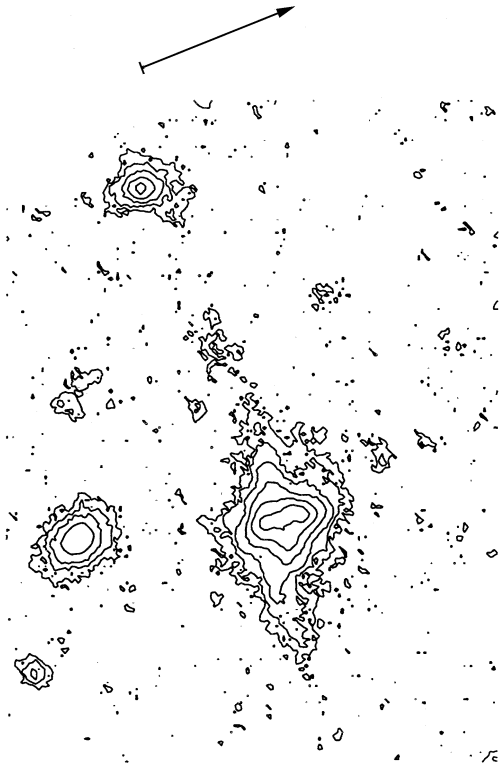

Fig. 2. Isophotal contour map of 2-809 constructed from the summed F606W+F814W frame. The faintest contour corresponds to 2σ of the sky level, isophotes step is $0.^{\rm m}75$. The arrow indicates north, east is $90^{\rm o}$ counterclockwise. The arrow length is 2″.

Approximate absolute "blue" magnitudes were found from the apparent b magnitudes using the K-correction from Cowie et al. (1994) for a "Sa-Sb" galaxy at this redshift for the main galaxy and for a "Sbc-Sdm" galaxy for the suspected ring. The correction between the instrumental b band and the standard B filter is used also according to Holtzman et al. (1995). Absolute luminosities of the central galaxy and the ring of 2-809 are close to that of local PRGs (Schweizer et al. 1983, Whitmore et al. 1987, Reshetnikov et al. 1994). (It should be noted that the derived absolute magnitudes must be considered as tentative only due to uncertain redshift and K-correction for the galaxy.)

Summarizing our analysis of the 2-809 photometric characteristics, one can conclude that in general this galaxy resembles well local PRGs with extended polar rings (Schweizer et al. 1983, Whitmore et al. 1987, Reshetnikov & Sotnikova 1997). As an alternative explanation of the 2-809 optical morphology one can propose that this galaxy is a "NGC 7252-like" merger

[2] The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166.

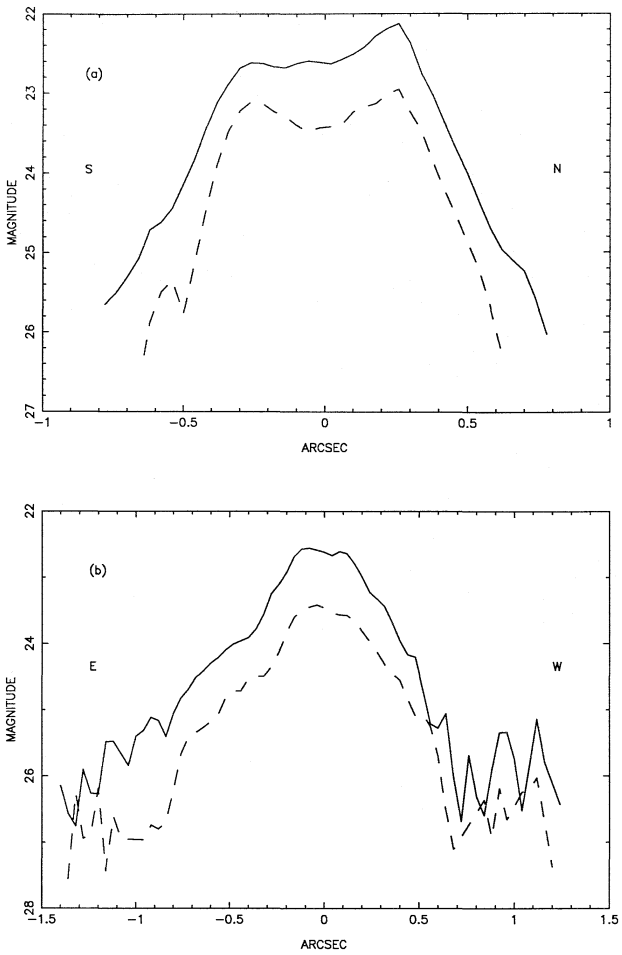

Fig. 3a and b. Liminosity profiles (in mag arcsec^{-2}) along the major axis of the central galaxy of 2-809 (**a**) and along the suspected polar ring (**b**) in the i (solid line) and v (dashed line) passbands.

with two symmetric tidal tails. Future spectral observations must clear up the true nature of this peculiar galaxy.

2.2. 2-906

Fig. 4 compares the morphology of the HDF galaxy 2-906 with the prototype polar-ring galaxy NGC 2685. The similarity between the galaxies is noticeable. The suspected ring in 2-906 has approximately the same diameter as the main galaxy and is inclined by about 75$^{\rm o}$ to its plane. The apparent axial ratio of the ring structure is about 0.5.

The galaxy has no published spectroscopic or photometric redshift (it is located near the edge of the chip and was omitted by Lanzetta et al. 1996). In order to estimate the redshift, we used a "differential" method: we chose galaxies with determined photometric redshifts from Lanzetta et al. (1996) in the interval 23.0 $\leq i \leq$ 24.0; selected in this sample the galaxies with "exponential-like" surface brightness distribution in the i passband similar to surface brightness distribution in 2-906 (see further); we considered for these galaxies relationships between observational colours and estimated redshift and examined the 2-906 characteristics position. We found distinct non-linear dependence between z and colour $b-v$ for the sample galaxies (see Fig. 5) and from the integral colour of the galaxy we estimate the redshift as 1.2. (This redshift does not contradict the other colours dependences on z also.) Naturally, this redshift estimation is very uncertain and we will use it with illustrative purpose only.

Table 2. Derived characteristics of the polar-ring candidates

	2-809	2-906
Adopted redshift	0.64	1.2
Central galaxy		
Total magnitude (i)	23.6	23.85
Absolute blue magnitude	-18.6: (-18.3:)	-21.5: (-21.0:)
$v-i$	+0.9	+0.6
$b-v$	+1.1	+0.25
Diameter (μ_i =26)	9.6 (8.3) kpc	11.5 (8.9) kpc
Position angle	174$^{\rm o}$:	124$^{\rm o}$
Axial ratio	0.6:	0.4:
Suspected ring		
Total magnitude (i)	24.4	24.6
Absolute blue magnitude	-17.4: (-17.1:)	-19.3: (-18.7:)
$v-i$	+0.8	+0.6
$b-v$	+0.4	+0.1
Diameter (μ_i =26)	31: (27:) kpc	11.5 (8.9) kpc
Position angle	81$^{\rm o}$:	48$^{\rm o}$
Ring to main galaxy luminosity ratio (i)	0.5	0.5

Fig. 6 presents isophotal contour map of the galaxy. The central galaxy shows peculiar structure - asymmetric surface brightness distribution and warped outer regions. In the i passband the galaxy reveals exponential-like surface brightness distribution (see Fig. 7) with exponential scalelenght of about 0.33″or 2.4 (1.9) kpc. This is typical value for present-day spiral galaxies (e.g., de Jong 1996). In the v passband the surface brightness is almost flat in the central region, which results in a strong $v-i$ colour gradient from the nucleus to galaxy periphery. The photometric cut along the major axis of the suspected ring (Fig. 7b) shows the asymmetry of the ring and its bluer colour in comparison with the central galaxy.

The general observational characteristics of the galaxy are summarized in Table 2. The main properties of 2-906 are quite consistent with the characteristics of local PRGs with relatively short polar rings (Schweizer et al. 1983, Whitmore et al. 1987, Reshetnikov & Sotnikova 1997). One can mention only a somewhat brighter absolute luminosities of the galaxy and the ring (absolute blue luminosities were estimated by the same manner as for 2-809 - see Sect. 2.1). This can be explained by uncertaintes in adopted redshift, K-correction and, probably, by active star formation in the central galaxy of 2-906.

3. Discussion

As it was shown in the previous section, the two HDF polar-ring candidates resemble well the general photometric and morphological properties of local PRGs. The main difference between local and distant PRGs is the structure of the host galaxy. Both

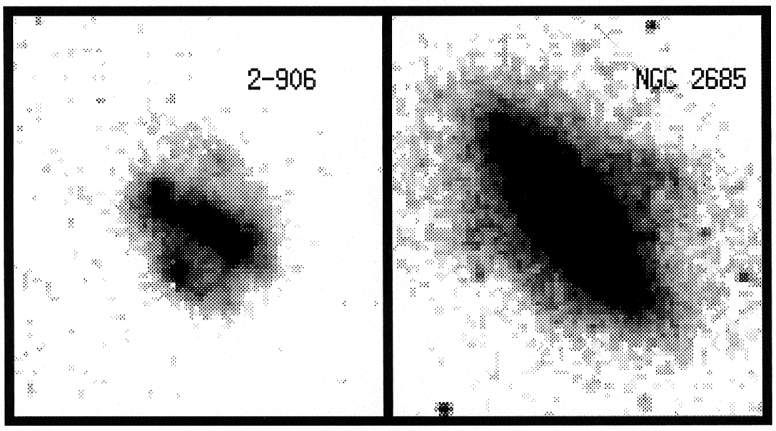

Fig. 4. Deep (F606W+F814W) image of 2-906 (left). The size of the image is $3.2'' \times 3.5''$. Right – Digital Sky Survey image of NGC 2685 ($2.3' \times 2.5'$.) Both images are in arbitrary orientation.

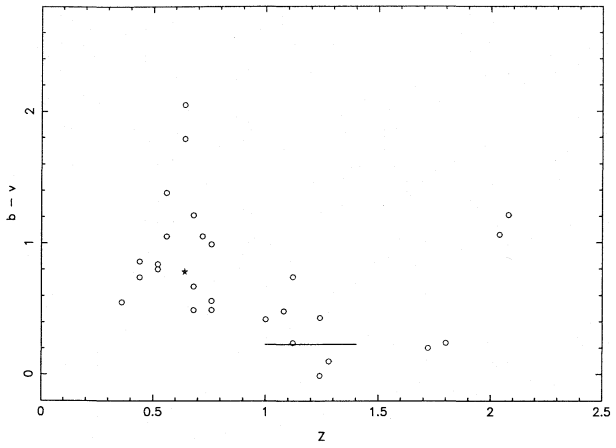

Fig. 5. Dependence of the observed colour $b - v$ for the HDF galaxies with exponential-like surface brightness distribution and total magnitude $23.0 \leq i \leq 24.0$ on the photometric redshift according to Lanzetta et al. (1996) (circles). The solid line segment shows location of the 2-906 colour, the star represents 2-809.

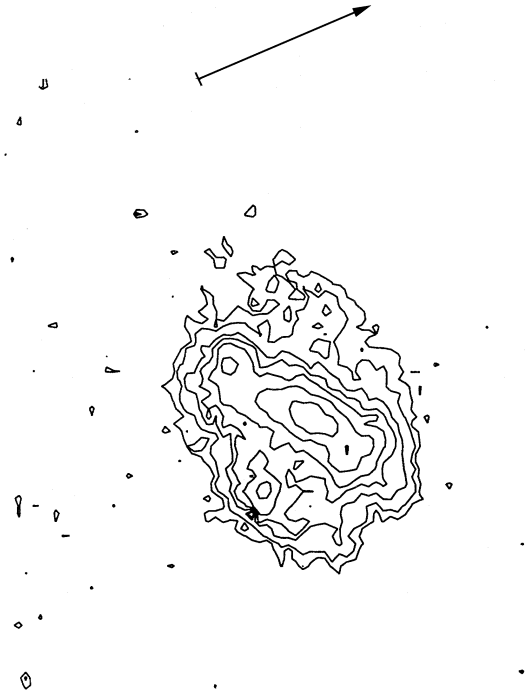

Fig. 6. Isophotal contour map of 2-906 from the combined F606W+F814W frame. The faintest contour corresponds to 2σ of the sky level; the fist three isophotes are separated by $0.^{\rm m}5$, then the isophotes step is $0.^{\rm m}3$. The arrow indicates north, east is $90^{\rm o}$ counterclockwise. The arrow length is $1''$.

polar-ring candidates show peculiar main bodies while local PRGs are usually gas-free early-type galaxies. One can propose that the observed central galaxies peculiarities are due to strong tidal shaking and matter accretion during the rings formation. A few billions years later - in the present epoch - after the gas consumption in star formation, the central galaxies become early-type looking galaxies.

The presence of two good polar-ring candidates in the small HDF is very interesting and probably provides some information about the frequency of galactic interactions at middle ($z \approx 1$) redshifts. Following Lavery et al. (1996), we estimate the likelihood of finding a single polar-ring galaxy in the HDF for two models: (1) a polar-ring galaxy volume density does not change with redshift (the nonevolving case) and (2) a polar-ring volume density increases with redshift (the evolving case).

In our calculations we have assumed that PRGs lie between the redshifts 0.5 and 1.5. According to PRC, 0.5% of all local S0 galaxies appear to have polar rings. (We did not correct this estimation for selection effects since in the first-order approximation the same selection effects must reduce the observed fraction of PRGs in the HDF also. Note, for instance, that the HDF galaxies are observed with the same orientation as local PRGs - edge-on central galaxies and almost edge-on suspected rings. See discussion about polar ring recognizion in the PRC.) Therefore, adopting that local S0 galaxies constitute about 1/10 of all galaxies and that the volume density of non-dwarf galaxies in the present epoch is 0.01-0.02 $\rm Mpc^{-3}$, we obtain the estimation of the local PRGs volume density as $(5 - 10) \times 10^{-6}$ $\rm Mpc^{-3}$.

Then, varying H_0 from 50 to 100 km/s/Mpc and q_0 from 0.05 to 0.5, we found that the probability of detecting a single PRG in the HDF is, on average, 0.06 ± 0.02 only for the nonevolving case. In the second case, assuming that the polar-ring galaxy volume density increases with redshift as $(1+z)^{4-4.5}$, we found

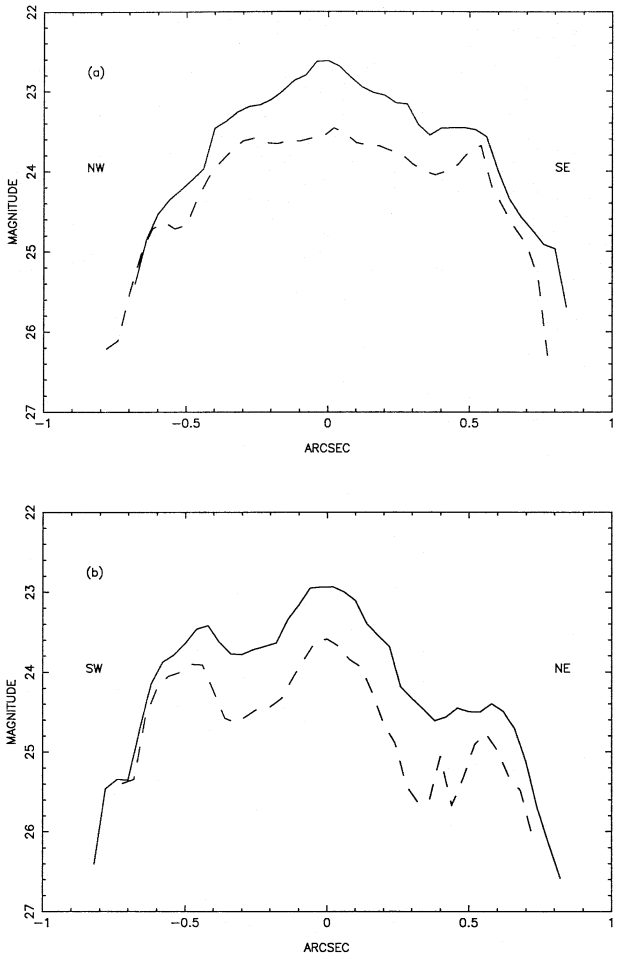

Fig. 7a and b. Luminosity profiles (in mag arcsec^{-2}) along the major axis of the central galaxy of 2-906 (P.A. = 124°) (**a**) and along the suspected polar ring (P.A. = 48°) (**b**) in the i (solid line) and v (dashed line) passbands.

that the expected number of PRGs is 1.6 ± 1.0. Thus, in the evolving case the expected number of galaxies is consistent with observations. Therefore, the PRGs presence in the HDF suggests that the volume density of PRGs does increase with redshift and provides evidence of a steeply increasing galaxy interaction rate (leading to a polar ring formation) up to $z \approx 1$. This conclusion is in accordance with recent statistics of distant ring galaxies. According to Lavery et al. (1996), a surprisingly large number of ring galaxy candidates in a random field suggests a rapid increase of a galactic interaction rate with redshift. (Let us note also that our adopted local volume density of PRGs is close to that for ring galaxies according to Few & Madore 1986. Therefore, one can expect to find a several ring galaxies in the HDF also.)

Another way (more rough but straightforward) of estimating the fraction of PRGs in the HDF - ratio the number of candidates by the number of galaxies in the HDF that are resolved enough to identify a polar ring - leads to the same conclusion about evolution of the volume density of PRGs. The fact that both candidates are 24th magnitude (v filter) suggests that we may not be able to identify PRGs much fainter than that. Assuming that we can identify a polar ring in all HDF galaxies with $v < 25.5$, we have relative fraction of PRGs as $\approx 2/300 = 0.7\%$. This relative fraction is significantly higher than local value of about 0.05% (Whitmore et al. 1990).

It should be noted, however, that present statistics of PRGs must be considered with caution. Both HDF candidates must be confirmed as true PRGs by kinematical observations. Moreover, the HDF polar rings are, probably, relatively young objects (from asymmetry of surface brightness and colour distributions) while among local PRGs there are old (for instance, A 0136-0801) and more recently formed rings (probably, NGC 4650A). Some local PRGs may be formed several 10^9 yr ago and, therefore, the statistics of present-day polar rings do not reflect local rate of galaxy interactions. Taking into account relatively young local PRGs only, we will have an evidence of even more rapid increase of the galactic interaction rate with z. Some additional limitations of such approach - estimation of the galactic interaction rate at high z from the statistics of a specific interaction relics - are discussed by Lavery et al. (1996).

4. Conclusions

Visual inspection of the HDF has revealed two relatively bright peculiar objects (2-809 and 2-906) morphologically resembling local polar-ring galaxies. We find that these objects are very similar to classic PRGs by general photometric characteristics. The presence of these objects in the HDF suggests that the volume density of PRGs does rise with redshift and supports a steeply increasing galaxy interaction rate at $z \approx 1$.

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