HUDF 1619 – a candidate polar-ring galaxy in the Hubble Ultra Deep Field

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A good candidate for a polar-ring galaxy has been detected in the Hubble Ultra Deep Field (HUDF). The galaxy HUDF 1619 ($V \sim 25^m$, $z \sim 1$) is the most distant object of this type known to date. A large-scale structure crosses the highly warped disk of the main galaxy seen almost edge-on at an angle of about 70°. The luminosity of this structure (the possible polar ring) reaches 1/3 of the luminosity of the central galaxy. A strong absorption lane is seen in the region where this structure is projected onto the disk of the central object. There are two galaxies of comparable luminosity adjacent to HUDF 1619 (in projection). One of them may be the donor galaxy in the interaction which gave rise to the ring structure.

**Keywords:** galaxies, groups and clusters of galaxies, intergalactic gas, polar-ring galaxies

1. Introduction

Polar-ring galaxies (PRGs) belong to a very rare and, in many respects, interesting class of objects (Whitmore et al. 1990). The unusual structure of such galaxies is commonly attributed to external accretion and interaction between galaxies. Therefore, if these processes were more frequent in the Universe in the past, one may expect the fraction of PRGs to increase with redshift. Only two candidates for distant objects of this type detected in the Northern Hubble Deep Field are known to date (Reshetnikov 1997).

In this paper, we describe a galaxy found in the Hubble Ultra Deep Field. Judging by the set of its morphological and photometric features, it is a good candidate for a distant ($z \sim 1$) PRG. The detection of this object is consistent with the assumption that the space density of the galaxies of this type increases with $z$.

2. The galaxy HUDF 1619 in the Hubble Ultra Deep Field

2.1. The Hubble Ultra Deep Field

The Hubble Ultra Deep Field (its standard abbreviation is HUDF) is the deepest optical image of a sky region obtained to date (Beckwith et al. 2006). The HUDF (its area is about 11 sq. arcmin.) was observed with the Hubble Space Telescope using the Advanced Camera for Surveys (ACS) in the F435W ($B_{435}$), F606W ($V_{606}$), F775W ($i_{775}$), and F850LP ($z_{850}$) broadband filters (the three digits in the filter names indicate the central wavelength in nanometers). Several hundred HUDF frames were taken from September 2003 through January 2004; the total exposure time was about 40\textsuperscript{h} in the $B_{435}$ and $V_{606}$ filters and almost 100\textsuperscript{h} in the $i_{775}$ and $z_{850}$ filters.

The resulting HUDF images at 0.\textquoteleft\textquoteleft03 steps are publicly accessible at the site of the Space Telescope Science Institute (STScI). Objects as faint as $\sim 30^m$ are identified in the field; the actual angular resolution is $\sim 0.\textquoteleft\textquoteleft1$. 

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2.2. The galaxy HUDF 1619

The optical morphology of HUDF 1619 (the number in the name is the galaxy number in the catalog by Beckwith et al. (2006) for the $i_{775}$ band) is typical of PRGs (Figs. 1 and 2): a large-scale structure seen almost edge-on crosses the stellar disk also seen almost edge-on at an angle of about $70^\circ$. An absorption lane is clearly seen in the region where the inclined structure crosses the disk of the central galaxy. Both, the galaxy itself and the possible polar ring look symmetric; their centers virtually coincide. These features allow us to classify the object as a ”good candidate for a PRG” (by the terminology of Whitmore et al. 1990). Most of the previously studied nearby candidates for PRGs with similar morphology, e.g. NGC 660 (van Driel et al. 1995) and UGC 9562 (Reshetnikov and Combes 1994), actually turned out to be PRGs. This suggests that HUDF 1619 is with high probability a PRG. The main parameters of HUDF 1619 taken from the literature or found by us are collected in the table.

The galaxy has no published spectroscopic redshift. The project of slitless spectroscopy for HUDF objects (the Grism ACS Program for Extragalactic Surveys – GRAPES; Pirzkal et al. 2004) provides a spectrum of the galaxy, but it shows no distinct features that could be used to estimate $z$. The COMBO-17 catalog (Wolf et al. 2004) contains no estimate of the photometric $z$ for the galaxy, but it provides the position of the peak in the probability distribution for possible values of $z$. This peak lies at $z = 0.7$. On the other hand, Coe et al. (2006) have recently given a photometric redshift of 1.3 for HUDF 1619. In what follows, we assume the galaxy to be at $z = 1.3$. (If we take $z = 0.7$, then all of the linear sizes mentioned below should be reduced by 15% and the absolute magnitude of the galaxy with the $k$ correction applied will increase, i.e., the galaxy will be fainter, by about 2$^m$).

The outer disk of HUDF 1619 demonstrates a significant integral-shaped warp of the plane with an amplitude of $\approx 14^\circ$ (see Figs. 1 and 2). Figure 3 shows photometric profiles of the galaxy along the major axis of the central part of its main body. The profiles exhibit a central dip in the brightness distribution that is associated, at least in part, with the proto-

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1 In this paper, we take $H_0=70$ km/s/Mpc, $\Omega_m=0.3$, $\Omega_\Lambda=0.7$.
2 All magnitudes here are given in the AB magnitude system.

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Fig. 1. HUDF 1619 images with different contrasts to highlight its main morphological features. The size of each frame is $1.8'' \times 1.8''$. North is at the top and east is on the left.
Table 1. Main parameters of HUDF 1619

| Parameter                                      | Value          | Source       |
|-----------------------------------------------|----------------|--------------|
| Coordinates: \( \alpha \) (2000)             | 53\,\textdegree\,1782428 | (1)          |
| \( \delta \) (2000)                          | -27\,\textdegree\,8076190 | (1)          |
| Object’s position in final HUDF frames:       |                |              |
| \( X \) (pixels)                             | 3580.5         | (1)          |
| \( Y \) (pixels)                             | 3305.6         | (1)          |
| Spectral type                                 | Scd–Im         | (2)          |
| \( B_{435} \)                                 | 25.38          | (1)          |
| \( B_{435} - V_{606} \)                      | +0.19          | (1)          |
| \( V_{606} - i_{775} \)                      | +0.32          | (1)          |
| \( V_{606} - z_{850} \)                      | +0.87          | (1)          |
| Redshift (\( z \))                           | 1.3            | (2)          |
| Absolute magnitude (\( M(B) \))              | -20\,m         |              |
| Optical diameter                              | 1.\"3 (11 kpc) |              |
| Radial disk scalelength (\( h_r \))         | 0.\"13 (1.1 kpc) |             |
| \( L_{ring} / L_{galaxy} \) (\( i_{775} \) filter) | 0.35  |              |

(1) – Beckwith et al. (2006)
(2) – Coe et al. (2006)

Fig. 2. Isophotal map of HUDF 1619 at 0.\".5 steps in the \( i_{775} \) filter. The image of the galaxy was restored by Lucy’s method (20 iterations). Arcseconds are along the axes.

The observed luminosity of the possible inclined ring structure reaches \( \sim 1/3 \) of the luminosity of the central galaxy. The mean color indices of the ring are close to those of the central galaxy, but their distribution is asymmetric: the southeastern (SE) part of the ring is bluer than its northwestern part by 0.\".1–0.\".2 (this applies to all color indices).

The observed vertical structure of the disk of the galaxy can also be described by an exponential model with \( h_z \approx 0.\".04 \). However, this is the observed value distorted by instrumental broadening. Since the FWHM sizes of the HUDF stellar images are 0.\".08–0.\".09 (Beckwith et al. 2006), the true vertical scale height should be smaller. (Recall that \( h_z \) is not the size of a particular structure, but a characteristic of the slope of the brightness distribution.) Having modeled the effect of instrumental broadening on the brightness distribution for HUDF galaxies of various sizes and thicknesses (this was done in the same way as in Reshetnikov et al. 2003), we found that \( h_r \) for HUDF 1619 remains virtually unchanged, while the vertical scale height should be reduced by a factor of 2.5, i.e. its undistorted value is \( h_z \approx 0.\".015 \approx 0.13 \) kpc. Consequently, the true ratio for the galaxy is \( h_r / h_z = 9 \), typical of nearby spiral galaxies (see, e.g., Fig. 6 in Reshetnikov et al. 2003).

The observed luminosity of the possible inclined ring structure reaches \( \sim 1/3 \) of the luminosity of the central galaxy. The mean color indices of the ring are close to those of the central galaxy, but their distribution is asymmetric: the southeastern (SE) part of the ring is bluer than its northwestern part by 0.\".1–0.\".2 (this applies to all color indices).

Figure 4 shows the distribution of about two thousand spiral and starburst galaxies in the color \( V_{606} - z_{850} \) and \( B_{435} - V_{606} \) – photometric redshift diagrams from Coe et al. (2006). The curves indicate the color evolution models from Elmegreen and Elmegreen (2006). The models assume that the star formation began at \( z = 6 \) and the initial metallicity was 0.008
Fig. 3. Photometric profiles of the galaxy along the major axis of its central body (P.A.=40°). The solid, dotted, and dashed curves are for the $z_{850}$, $i_{775}$, and $V_{606}$ filters, respectively.

(0.4$Z_{\odot}$). The star formation lasted 1 Gyr and the star formation rate decreased over this time exponentially with a time scale of 0.3 Gyr (upper curves) or remained constant (lower curves). The color indices for most galaxies, including HUDF 1619 (large filled circles), are located between the two curves, showing a trend in the color–$z$ plane close to that expected in the model. Comparison of the color indices for HUDF 1619 with those of other edge-on HUDF galaxies and with model calculations shows that active star formation is under way and young stars with ages $\leq 1$ Gyr are present in the galaxy itself and in the inclined ring (Elmegreen and Elmegreen 2006).

3. Discussion and conclusions

One of the most obvious PRG formation scenarios is the capture of matter in a circumpolar orbit during an encounter of two galaxies. Objects in the process of such a capture are observed directly (e.g., NGC 3808A,B) and, in addition, this scenario has repeatedly been tested by numerical simulations (Reshetnikov and Sotnikova 1997; Bournaud and Combes 2003; Reshetnikov et al. 2006). If the structure of HUDF 1619 is explained by the interaction with another galaxy, then the donor galaxy should be relatively close to HUDF 1619.

In a field with such a high projected density of objects (~10,000 galaxies or about one object per 2″ × 2″ field are identified in the HUDF), candidates for spatially close neighbors can be found near any galaxy. Thus, for example, there is a strongly perturbed galaxy, HUDF 1775, 4″ (or 33 kpc at $z = 1.3$) to the north of HUDF 1619. Its apparent magnitude is comparable to that of HUDF 1619 and it exhibits a structure resembling a highly bent tidal tail. However, no spectroscopic $z$ value is available for this galaxy and, just as for HUDF 1619, the COMBO-17 catalog (Wolf et al. 2004) gives no photometric $z$ estimate for it. The $z$ estimate from Coe et al. (2006) ($z = 2.04$) removes this galaxy from the list of potential donors, however, this estimate may be inaccurate.

A compact and slightly asymmetric galaxy (HUDF 1607), which is about 1″ fainter than HUDF 1619 in the $V_{606}$ and $i_{775}$ filters, lies approximately 2.″2 (18 kpc at $z = 1.3$) to the west of HUDF 1619. According to Coe et al. (2006), $z = 1.3$ and, hence, this galaxy may be considered as a candidate for a donor galaxy. To ultimately clarify the question of whether HUDF 1607 (and, possibly, HUDF 1775) is physically associated with
HUDF 1619, accurate redshifts of the galaxies must be determined.

Thus, we detected a galaxy in the HUDF that closely resembles PRGs observed in the local Universe. Previously, two more candidates for PRGs were identified in the Northern Hubble Deep Field (Reshetnikov 1997) at redshifts of 0.271 and 0.498 (Cohen et al. 2000). The Southern Deep Field also contains objects that are morphologically similar to PRGs, but they can be attributed to this class with lesser confidence. Can any conclusions about the evolution of the PRG space density be reached if three objects are observed in three deep fields? (Given the difficulty of classifying distant PRGs, this number may be considered as a lower limit for their actual number.)

Let us use the parametrization of the space density evolution in the form \((1 + z)^m\) and assume the local PRG density to be \(3.5 \times 10^{-5} \text{ Mpc}^{-3}\) (this estimate was obtained by applying the standard \(V/V_{\text{max}}\) method to the objects of categories A and B in the PRG catalog by Whitmore et al. 1990). Then, \(m = 1.2\) will correspond to the three objects observed in the \(z\) range from 0.1 to 1.3 in the direction of the three deep fields (their total area is \(1.8 \times 10^{-6} \text{ sr}\)). If, however, the galaxy HUDF 1619 is assumed to be not at \(z = 1.3\), but at \(z = 0.7\) (see above), then our \(m\) estimate will increase to 5.1. This may be indicative of fast evolution of the PRG density.

The above estimates show that the PRG statistics can become a useful tool for estimating the rate of interactions and mergers of galaxies at earlier epochs. However, this requires both accurate, spectroscopic \(z\) estimates and a further increase in the number of such objects among distant galaxies.

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