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KINEMATICS OF AN "E+A" GALAXY IN ABELL 665 AT $z = 0.18$[1]

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ABSTRACT

The first profiles of rotational velocity and velocity dispersion are presented of a blue "Butcher-Oemler" galaxy in an intermediate-redshift cluster, Abell 665, at $z = 0.18$. A deep, high spectral resolution spectrum shows that the galaxy rotates rapidly, with an observed rotation speed of 180 km s^{-1}. A lower resolution spectrum clearly shows that the galaxy has two population components, a young component resembling an A star spectrum, and an old component resembling a K star spectrum. This galaxy is therefore similar to "E+A" galaxies discovered previously by Dressler & Gunn in intermediate-redshift clusters. The luminosity profiles and kinematics of the two components are quite similar. The younger component is possibly more extended, and may be rotating faster in the center. This blue galaxy shows a large residual from the Faber-Jackson relation for the red galaxies in the same cluster. If it were an ordinary elliptical, it would be too bright by 2.2 ± 0.5 mag in the I band. This is much larger than can be explained by the contribution of the young component. The Tully-Fisher relation implies a much smaller discrepancy of 0.3 ± 0.3 mag. All the data are consistent with the hypothesis that the E+A galaxy is a disk galaxy, which is evolving into a cluster spiral or an S0 galaxy with low star formation rate at $z = 0$. There appear to be many possible counterparts in a nearby rich cluster like Coma.

Subject headings: galaxies: evolution — galaxies: kinematics and dynamics — galaxies: photometry

1. INTRODUCTION

Direct observational studies of galaxy evolution are difficult because of the faintness and small apparent size of distant galaxies. It is virtually impossible to obtain resolution and signal-to-noise ratio on galaxies at $z = 0.5$ comparable to those obtainable for nearby ones. Nevertheless, studies of galaxies in distant clusters and the field have shown surprising results. In particular, Butcher and Oemler demonstrated in their pioneering work that rich clusters at intermediate redshifts contain unusually high fractions of blue galaxies (Butcher & Oemler 1978, 1984). This blue population is absent in nearby rich clusters. Follow-up studies by Dressler & Gunn (1983) and others have confirmed these results (e.g., Couch & Sharples 1987; Gunn & Dressler 1988; Fabricant, McClintock, & Bautz 1991). These authors found blue galaxies with spectral characteristics of normal spiral and "E+A" galaxies. Galaxies in this last class show indications of both a relatively young component (the A star, or "A" component, 1 Gyr old) and an old component (the elliptical, or "E" component), but no evidence for strong ongoing star formation. These types were not predicted to exist in the "normal" models of galaxy evolution, and such galaxies have been interpreted to be poststarburst galaxies.

The morphological type of the blue galaxies has been uncertain. Early imaging studies by Thompson (1986, 1988) indicated that they have significant disks. These conclusions were qualitatively confirmed by Lavery & Henry (1988) and Lavery, Pierce, & McClure (1992), who also found many apparently interacting systems among the blue objects. Recent *Hubble Space Telescope* (*HST*) images taken by Dressler et al. (1993) show pronounced spiral structure in many blue systems, and some of the poststarburst galaxies appear to be mergers.

It is clear that our understanding of the evolution of distant galaxies would benefit from additional information. For that reason I have started a program to measure intrinsic velocity dispersions of galaxies at intermediate redshifts. The velocity dispersions can be used to measure the passive stellar evolution of the normal galaxy population, and can help to constrain the relevance of mergers and starbursts in galaxy clusters (Franx 1993b).

The first results of the program are reported in this *Letter*. High signal-to-noise ratio, high spectral resolution observations have been obtained on galaxies in the rich cluster Abell 665 at $z = 0.18$. Quite unexpectedly, one of the brightest galaxies in the cluster has an E+A spectrum. A detailed study of this particular galaxy is presented here. In § 2 the spectroscopic data are presented, with profiles of rotation velocity and velocity dispersion. The photometry is discussed in § 3. A general discussion is given in § 4.

2. SPECTROSCOPIC OBSERVATION ON ABELL 665

The rich cluster Abell 665 at $z = 0.18$ was selected for study because of its redshift, richness, and location on the sky. An R-band image and a list of galaxy positions were kindly made available by M. Birkinshaw. The richness of the cluster allowed efficient observations with a multislit mask at the focal plane of the Red Channel Spectrograph at the MMT (see Fabricant et al. 1991).

Galaxies were selected from the R-band image. They were chosen by their flux through a $1''.6 \times 8''$ slitlet. During the first run in 1991 January, spectra were taken with a spectral resolution of 4 Å and were centered on the redshifted Mg b lines at a rest wavelength of 5170 Å. The total integration time was 9 hr. During an observing run in 1992 March, low-

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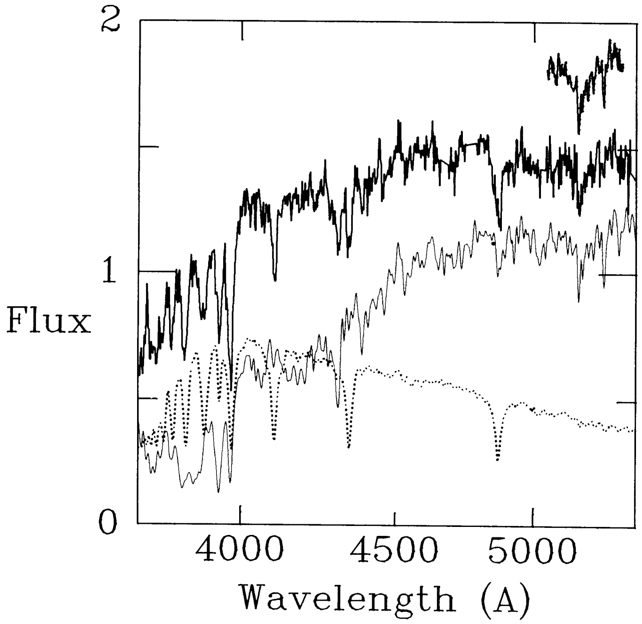

FIG. 1.—Low-resolution spectrum of the bright E+A galaxy in Abell 665 at $z = 0.18$ (*heavy curve*). A spectrum of an A star (*dotted curve*) and a K star (*thin curve*) are drawn. The galaxy spectrum is well approximated by the summation of these two spectra. The offset spectrum in the upper right-hand corner is the high-resolution spectrum from which the kinematics are determined.

resolution spectra were taken with a total integration time of 2 hr. The seeing was between 1″ and 1″.5 during the observations.

The spectra were reduced with the standard IRAF reduction software. Since the galaxies are clearly extended, each slitlet spectrum was reduced as a separate, long-slit spectrum. The end products of the reduction were fully calibrated, rectified, sky-subtracted two-dimensional spectra.

The low-resolution spectrum of galaxy 3 is shown in Figure 1. It clearly shows the characteristic E+A signature, as found earlier by Dressler & Gunn (1983) in other distant cluster members. There are no oxygen or hydrogen emission lines visible in the spectrum, indicating that the current star formation rate must be low. The galaxy spectrum can be modeled as a superposition of an A star spectrum and a K star spectrum. The high-resolution spectrum in Figure 1 shows the weak Mg *b* and Fe absorption lines. Since A stars do not have any strong spectral features in this wavelength interval, the kinematics of the old component can be derived reliably from the high-resolution spectra.

The kinematics were determined with the standard Fourier fitting method (Franx, Illingworth, & Heckman 1989). Special care was taken to construct a template star spectrum with the correct resolution. The high redshift of the galaxy makes it impossible to obtain a proper template spectrum with the same grating. A different grating tilt is necessary to obtain stellar spectra of the same wavelength region. Such spectra have the same spectral resolution (in Å) as the spectra taken on the redshifted galaxies but have different velocity resolution (in km s^{-1}, by $1 + z$). Hence, an absolute determination of the instrumental resolution was necessary. This was achieved by analysis of the calibration spectra and sky lines. A high-resolution stellar spectrum kindly made available by K. Kuijken was degraded to obtain a template spectrum. This template spectrum then corresponds to that of a single K star at $z = 0.18$, as required.

The resulting kinematics are presented in Figure 2. Surprisingly, it was possible to derive profiles of rotational velocity and velocity dispersion, exceeding the expectations of the author. The high rotation and low velocity dispersion of the galaxy demonstrate that this galaxy is not a typical giant elliptical. The most plausible explanation of the high rotational velocity is that the galaxy has a disk component. Simulations of the effects of seeing indicate that the rotation curve is not resolved within 2″ from the center. At larger distances, the seeing effects are small. A model with an asymptotic rotational velocity of 180 km s^{-1} and a central velocity dispersion of 150 km s^{-1} fits the observations well after convolution with the point-spread function.

The low-resolution spectra cover a much larger wavelength range, and include absorption lines from both the young and the old components (see also Fig. 1). Although the resolution is too low to determine velocity dispersions, it is possible to derive rotational velocities for the separate components, as shown in Figure 3. These velocities were derived by a least-squares fit, with the velocities and relative light contributions of both components as free parameters. In order to obtain reliable velocities, the continuum was subtracted before the fit. The old component was modeled by a K0 giant star, the young component by an A5 main-sequence star. The spectra were taken from Jacoby, Hunter, & Christian (1984) and convolved to the instrumental resolution. Figure 3*a* shows the relative contributions from the two components. Since the continuum was subtracted before the fit, the two components do not necessarily add to unity. The measurements are effectively

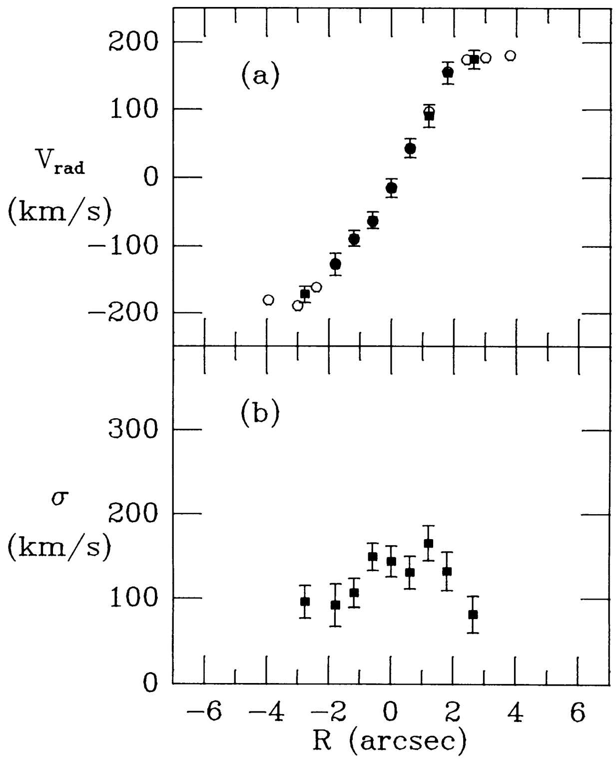

FIG. 2.—Kinematics of the old component in the E+A galaxy. (*a*) Radial velocity and (*b*) velocity dispersion, as a function of radius along the slit. Note the rapid rotation and low velocity dispersion. Closed symbols denote the results from the full Fourier fit; open symbols denote the radial velocities from a cross-correlation fit. The cross-correlation fit can give reliable velocities at low signal-to-noise ratio in the outer parts and shows that the rotation curve levels off at 180 km s^{-1}.

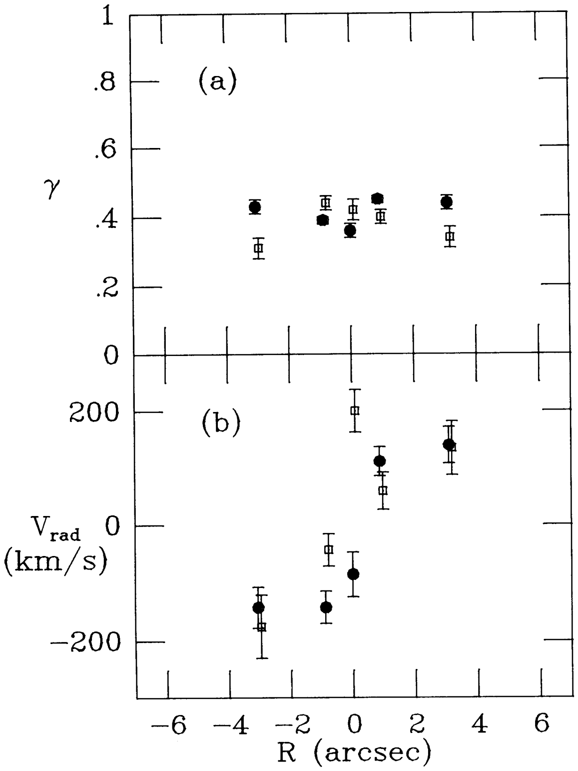

FIG. 3.—(*a*) Relative line strengths of the old component (*open symbols*) and the young component (*closed symbols*) as a function of radius along the slit. (*b*) Radial velocities of the two components along the slit. The kinematics and structure of the two components are quite similar. The young component may be somewhat more extended, and may be rotating faster in the center. Given the seeing of $\approx 1\farcs5$, the four radial samples outside the nucleus are independent.

measurements of the line strengths. To first order, the line strengths are constant. There is an indication that the line strengths of the A component increase slightly with radius and that the line strengths of the K component decrease somewhat. Figure 3*b* shows that the rotation of the two components is also similar, except for a marginally steeper rise of the rotation curve of the A component. The results are consistent with the K component originating from an old disk and small bulge and the A component originating from a young disk component. This interpretation is still somewhat uncertain, however. Line-strength gradients are known to exist in early-type galaxies (e.g., Gorgas, Efstathiou, & Aragon Salamanca 1990) and are at least partly due to metallicity gradients. Data with higher signal-to-noise ratio are required to confirm the rotational differences between the two components.

3. PHOTOMETRY ON ABELL 665

Following the detection of the E + A galaxy in Abell 665, photometry of the cluster was obtained at the KPNO 2.1 m telescope in 1991 December. The E + A galaxy is 0.8 mag bluer in $B-I$ than most of the other cluster members. Several galaxies in the vicinity of the E + A galaxy have similar blue colors. An isophotal map of the galaxy, and its nearby neighbors, is presented in Figure 4.

This deep *R* image of the blue galaxy was analyzed with the isophote fitting routines written by the author and described by Jørgensen, Franx, & Kjærgaard (1992). The intensity profile can be described well by an exponential, with a scale length of $1\farcs6$, or 6.5 h_{50}^{-1} kpc. The apparent ellipticity is 0.3 at large radii. Simulations of exponential disks convolved with the point-spread function indicate that the true apparent ellipticity is 0.35. The position angle changes with radius, and weak residuals from ellipses are visible. These structures could be due to spiral arms or possibly a bar.

Finally, relative magnitudes were derived for all program galaxies. Total fluxes within a 20 h_{50}^{-1} kpc radius were calculated. Velocity dispersions were taken from Franx (1993b), where details concerning the reduction procedure and errors are given. Figure 5 shows the Faber-Jackson relation for the cluster members at $z = 0.18$. While equivalent to the local Faber-Jackson relation (Faber & Jackson 1976), a direct comparison cannot yet be made in the absence of an absolute flux calibration. The blue galaxy lies significantly below the relation defined by the other cluster members. The galaxy is too bright by 2.2 ± 0.5 mag for its velocity dispersion. Part of the discrepancy must be due to the additional young component. This young component is expected to fade considerably after a few gigayears. However, even if the component contributes as much as 50% of the light at the Mg *b* band, the fading in the *I* band is only on the order of 0.4 mag.

Since there is evidence that the galaxy is a disk galaxy, the Tully-Fisher relation would be more appropriate to use (Tully & Fisher 1977). The circular velocity of the blue galaxy can be derived from the apparent mean rotation, after correction for inclination and asymmetric drift. An inclination of 51° ± 4° is derived from the apparent ellipticity of 0.35 ± 0.05. The asymmetric drift is calculated following Binney & Tremaine (1987). The resulting circular velocity is 280 km s^{-1}. The calculation was based on the assumption that $\sigma_\phi = \sigma_z = \sigma_R/\sqrt{2}$, and the radial dependence of σ_ϕ was derived from the data. If we assume isotropy, or if we ignore the measured velocity dispersions in the outer parts and use the relations found for nearby galaxies (Binney & Tremaine 1987), the result varies by ±4%. The total error in the circular velocity is estimated at 10%.

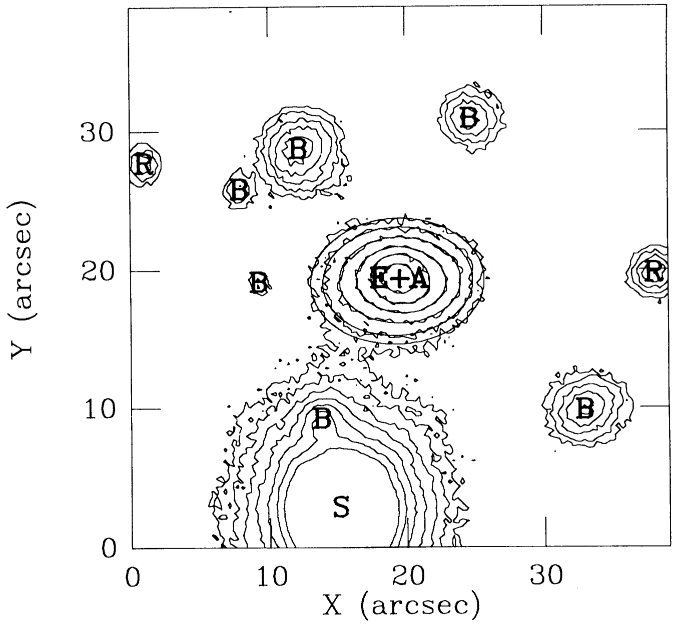

FIG. 4.—*R*-band image of the field centered on the blue E + A galaxy. The best-fitting ellipses to the galaxy are superposed on the raw isophotes. The blue galaxy shows a position-angle twist, and weak isophotal distortions, which may be caused by a bar and spiral arms. Blue and red galaxies are marked with a B and an R, respectively. The bright star is marked by an S. The high number of blue galaxies is evident.

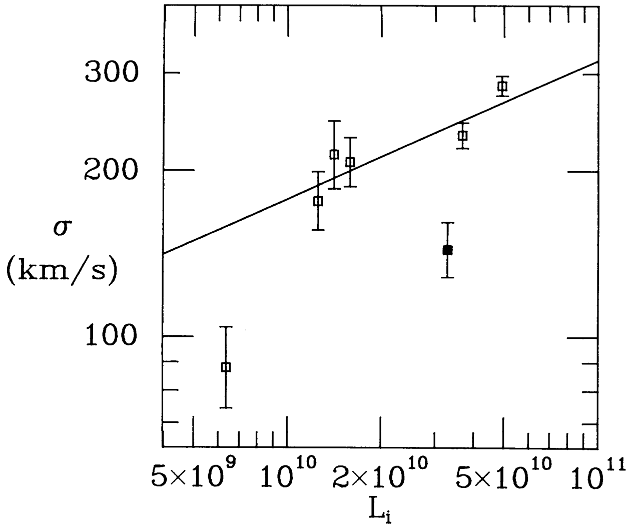

FIG. 5.—Faber-Jackson relation for a sample of cluster galaxies in Abell 665 at $z = 0.18$: the central velocity dispersion is plotted against I luminosity (arbitrary units). The line is the best-fitting relation of the form $L \propto v^4$. The E+A galaxy is indicated by the closed symbol and is excluded from the fit. It has a residual of 2.2 ± 0.5 mag with respect to the Faber-Jackson relation.

Franx (1993a) has shown that elliptical galaxies satisfy the R-band Tully-Fisher relation for spiral galaxies in the Virgo Cluster (Pierce & Tully 1988) if one uses $v_c = 1.26\ \sigma_*$ for the ellipticals. Using these results, the E+A galaxy is too bright by 0.3 ± 0.3 mag when compared with the Tully-Fisher relation calculated from the other ellipticals. Thus the agreement is much better if it is assumed that the galaxy is a disk galaxy.

4. DISCUSSION

We have presented photometry and spectroscopy on the bright, blue cluster member in Abell 665 at $z = 0.18$. The galaxy rotates rapidly, with a rather low velocity dispersion. The spectra can be decomposed into an A star component and a K star component, each of which contributes about 50% of the light. The young component could be somewhat less concentrated to the center and may be rotating faster near the center. This would be consistent with the superposition of an old component, consisting of a disk and a small bulge, and a young disk component. The result is in general agreement with other studies which concluded that many of the blue galaxies have disks (e.g., Thompson 1986; Dressler et al. 1993). The latter study has demonstrated the power of *HST* images for the classification of distant galaxies. Similar images of the blue galaxy in Abell 665 will be valuable to verify the classification.

The spectral characteristics of the blue galaxy are similar to the E+A galaxies found earlier by Dressler & Gunn (1983). There is no indication of ongoing star formation. Since this galaxy is likely to have a disk, and is not a regular elliptical, a spectral classification as "S0+A" is probably more appropriate. In fact, the neutral classification "K+A" would be the most suitable for such galaxy spectra, since it avoids issues of morphology.

Comparison with the Faber-Jackson relation for red cluster members in Abell 665 shows that the "K+A" galaxy is too bright by 2.2 ± 0.5 mag in the I band for its velocity dispersion. Even though the fading of the young component might reduce this by ≈0.4 mag, this is an extremely large residual. This suggests that the galaxy has a dominant disk component. The Tully-Fisher relation based on the circular velocity implies a lower residual of ≈0.3 mag.

The dynamical properties are unusual, but not exceptional for a disk galaxy. After the young component has faded, the galaxy will still be one of the largest and brightest cluster members. Counterparts in nearby clusters should be easy to identify. A possible counterpart in Coma is NGC 4921, a red Sb galaxy, which is the third brightest galaxy. Its J-magnitude of $m_J = 12.9$ is less than 0.7 mag fainter than that of NGC 4874, the brightest elliptical galaxy (Butcher & Oemler 1985), and it is dominated by its disk (Dressler 1980). Butcher & Oemler list 10 galaxies brighter than $m_J = 14$ in Coma, and four have bulges contributing 10% or less of the total light (Dressler 1980). Thus Coma may be abundant in possible counterparts to the bright blue galaxies in distant clusters.

The data imply that the blue galaxy has undergone significant morphological evolution in a relatively short period of time. If it is a disk galaxy, it probably appeared as a blue spiral galaxy before the transformation. It is now in a phase that is not expected to last longer than another gigayear, and it will evolve into a red spiral, or early-type, galaxy. These new data do not resolve the question as to the mechanisms responsible for the transformation. It is unlikely that a disk-dominated galaxy forms from a full-blown merger at $z = 0.2$, when much of the gas in large spiral galaxies has been converted into stars. Thus tidal interactions with nearby galaxies, accretion of gas or low-mass galaxies, or interaction with the intracluster medium (ICM) are candidates. Since the galaxy lies in a small concentration of blue galaxies, it is possible that tidal interaction between the galaxies in this group is responsible or that the group as a whole is falling into the ICM, and all member galaxies are affected by the ram pressure.

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