Identification and Morphologies of Galaxies with Old Stellar Populations at $z \sim 2.5$

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**Abstract.** We describe a study of morphologies of galaxies with old stellar populations in radio-source fields at $z \sim 2.5$. A significant fraction of these are dominated by disks of old stars, and none we have found so far has the properties of present-epoch ellipticals. Recent Spitzer IRAC data confirms that at least one of our prime examples is definitely not a reddened star-forming galaxy.

1. Introduction

Detailed studies of galaxies in the local universe and recent investigations of red-sequence galaxies at high redshifts both indicate that a significant fraction of massive galaxies formed at very early epochs and within a very short time span. It has also become increasingly clear that galaxy formation involves feedback effects that are extremely difficult to model realistically. As Silk (2000) has emphasized, “*Ab initio* calculations, beginning with inflationary fluctuations that evolve into mature galaxies, are currently a theorist’s dream and are likely to remain so.” In other words, models of galaxy formation need strong observational guidance to constrain the various possible theoretical scenarios.

We have had a program underway for some time now to isolate and investigate, at a few specific redshift ranges, galaxies that comprise the oldest stellar populations at each redshift. Even tiny amounts of residual star formation in a dominant old stellar population can drastically change the colors of a galaxy at short rest-frame wavelengths. Galaxies that show no evidence for such star formation are therefore quite rare, but they offer us the prospect of a clear view of processes that are likely to be important in massive galaxies generally. Our program is ultimately aimed at determining morphologies for a significant sample of such galaxies at high redshifts. Morphologies are important because they can preserve direct information relevant to formation mechanisms.

We shall use the term “old galaxies” (OGs) for galaxies that comprise stellar populations that, at their observed epoch, are already old and have virtually no admixture of recent star formation. We concentrate on identifying OGs that are in groups and clusters associated with radio sources, for two main reasons: (1.) radio source fields are likely to include regions of higher-than-average density in the early universe, in which the very first massive galaxies are likely to have formed (see, e.g., Best 2000; Barr et al. 2003); and (2.) looking for companions to radio sources *at a specific redshift* allows us to choose redshifts for which the photometric diagnostics from standard broadband filters give the cleanest possible separation between old galaxy populations and highly reddened star-
forming galaxies or other possible contaminants. We concentrate here on $z \sim 2.5$, for which the 4000 Å break falls between the $J$ and $H$ bands.

2. High-Resolution Imaging

The first example in this redshift range that we found was 4C 23.56 ER1 (Knopp & Chambers 1997). This galaxy, with passive evolution alone, would end up as a $\sim 2L^*$ galaxy at the present epoch. Our Subaru adaptive optics (AO) imaging and subsequent modelling with galfit (Peng et al. 2002) showed it to have very close to an exponential profile and a small axial ratio. The galaxy has every appearance of being an almost pure disk of old stars. Recent HST NICMOS images confirm these results.

We currently have reasonably good high-resolution (NICMOS or AO) imaging of 6 OGs at $z \sim 2.5$, almost all of which are similar in luminosity to 4C 23.56 ER1. None of these have the characteristics of normal ellipticals at the present epoch. We have space here to show only one new example, 4C 29.28 ER2, which is the closest to edge-on of several galaxies having low Sérsic indices (Fig. 1).

![Image](image.png)

Figure 1. Image and models of 4C 29.28 ER2. The left panel shows the Keck II LGSAO $K'$-band image, the 2nd panel shows the galfit model, the 3rd panel shows the residual of the subtraction of the model from the AO image, and the right panel shows the galfit model without convolution with the PSF. Insets show lower contrast versions of the images.

The left panel of Fig. 2 shows the spectral-energy distribution (SED) for 4C 29.28 ER2, which closely matches that for an instantaneous burst model for which all of the stars were formed when the universe was just $5 \times 10^8$ years old. The right panel shows the radial-surface-brightness profile, together with the best-fit $r^{1/4}$-law and Sérsic profiles. The profile confirms the visual impression of a nearly edge-on disk, with no hint of a significant bulge.

3. Dusty Star-Forming Galaxies?

At this point, it is natural to ask, “Couldn’t these be, after all, simply dusty star-forming galaxies?” Our photometric criteria are designed to minimize this possibility by insisting on a sharp break in the spectrum, as one sees in the left panel of Fig. 2. Nevertheless, the $H-K'$ baseline is fairly short, and it could be argued that, within perhaps 2σ, one might be able to fit a steeper curve through this region. In fact, Pierini et al. (2005) apparently simply assume that 4C 23.56 ER1 (Stockton et al. 2004) must be a dusty, star-forming galaxy.
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Figure 2. SED and radial-surface-brightness profile of 4C 29.28 ER2. (left panel)—The observed-frame SED (points with error bars). The gray trace is a 2.1-Gyr-old instantaneous burst [Bruzual & Charlot (2003)] model. (right panel)—The radial-surface-brightness profile ($r$ is the semi-major axis) of the Keck II LGSAO image shown in Fig. 1, with traces showing the best-fit $r^{1/4}$-law (light gray) and Sérsic (darker gray) profiles. An exponential profile would be virtually identical to the Sérsic profile.

We can explore this possibility in two ways. First, we can look at tracks of models of galaxies with old stellar populations and of models of dusty star-forming galaxies in the $H - K' - J - H$ diagram. An example is shown in the left-hand panel of Fig. 3. In this plot, the track of a [Bruzual & Charlot (2003)] instantaneous burst when the universe was $5 \times 10^8$ years old ($z \approx 10$) is plotted as a dotted line for redshifts from 1.6 to 3.0. Similarly, continuous-star-forming models with added dust such that $J - K' = 2.9$ are shown as a solid line. Our 6 OGs are plotted with their photometric errors. This diagram shows two things: (1.) few, if any, of our galaxies are actually within 2σ of these particular dusty star-forming models; and (2.) we have probably been missing significant numbers of galaxies that actually do have essentially unreddened old stellar populations in our fields because of the concern about including star-forming galaxies (i.e., all of our points are above and to the left of the OG locus).

A concern about this approach is that there can be a wide range of models for dusty star-forming galaxies, and we have only considered one. It is very difficult to be sure that no such model can match the data in this diagram.

Our second approach is simply one of extending our SED to longer wavelengths, such that any plausible dusty model should be distinguishable from an old stellar population. The first data from our Spitzer program on this sample is shown in the right-hand panel of Fig. 3. It clearly shows that the SED of 4C 23.56 is completely consistent with a very lightly reddened old stellar population, and so inconsistent with our assumed dusty star-forming model that it is almost certainly also inconsistent with any such model.

At this point, it appears that we may be stuck with the presence of massive disk galaxies of old stars in (at least) dense environments in the early universe, along with all the consequences: (1.) the existence of massive galaxies that have
formed essentially monolithically at very early times, (2.) rates of star formation of at least a few hundred $M_\odot$ per year, sustained for several $\times 10^8$ years (or higher rates over shorter periods), and (3.) the problem of the ultimate fate of such galaxies, which do not seem to be common at the present epoch.

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Figure 3. The left panel shows the location of $z \sim 2.5$ galaxies from our sample in the $H-K'$—$J-H$ diagram. The galaxies are represented as points with their photometric uncertainties. The dotted line shows the trace of solar-metallicity, instantaneous-burst Bruzual & Charlot (2003) models formed at $z = 10$ for redshifts ranging from 1.6 to 3.0. The solid line traces continuous star-forming models, with sufficient Calzetti et al. (2000) reddening added to give $J - K' = 2.9$, for the same range of redshifts. Circled points are at $z = 2.5$. The right panel shows optical, near-IR, and Spitzer IRAC photometry of 4C 23.56. The light gray curve is a continuous star-formation model reddened to roughly fit the optical and near-IR data. The dark gray curve is an extension of one of 3 SEDs given in Stockton et al. (2004) as fits to the optical and near-IR photometry alone. The IRAC points at 3.6, 4.5, 5.8, and 7.9 $\mu$m are not fits to the model and have not been scaled in any way, except for the standard aperture corrections given in the IRAC Handbook.