DISCOVERY OF AN EXTREMELY RED GALAXY AT $z = 0.65$ WITH DUSTY STAR FORMATION AND NUCLEAR ACTIVITY\footnote{Based on observations with the Infrared Space Observatory, Australia Telescope Compact Array, Anglo-Australian Telescope, Cerro Tololo Inter-American Observatory, and the European Southern Observatory (program 266.A-5633).}

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\begin{abstract}
In the course of the follow-up multiwavelength study of a deep radio survey, we have discovered that the millijansky radio source PDF J011423 is a low-redshift ($z = 0.65$) extremely red galaxy (ERG) with $K = 15.3$, $R-K = 5.8$, and $J-K = 3.1$. Optical, infrared, and radio photometry, together with optical and near-infrared spectroscopy, reveal a heavily obscured galaxy ($A_V = 5–6$, from the observed Balmer decrement) undergoing vigorous star formation and presenting an active galactic nucleus. PDF J011423 is a representative member of the dusty ERG population, providing a local counterpart for studying more distant ERGs.

\textit{Subject headings:} galaxies: active — galaxies: individual (PDF J011423) — galaxies: photometry — galaxies: starburst — infrared: galaxies — radio continuum: galaxies
\end{abstract}

1. INTRODUCTION

Deep multiwavelength near-infrared and optical surveys over the last decade have led to the discovery of a population of galaxies with very red optical-infrared colors ("extremely red galaxies" [ERGs]; e.g., Elston, Rieke, & Rieke 1988; McCarthy, Persson, & West 1992; Hu & Ridgway 1994; Thompson et al. 1999; Daddi et al. 2000). ERGs, defined as galaxies with $R-K > 5$, appear to fall into two subclasses: (1) high-redshift ($z \approx 1$) evolved elliptical galaxies with intrinsically red spectral energy distributions (SEDs; e.g., Spinrad et al. 1997; Stiavelli et al. 1999; Soifer et al. 1999) and (2) highly obscured dusty galaxies undergoing starburst activity (e.g., Cimatti et al. 1998; Dey et al. 1999; Smail et al. 1999). The predominance in the ERG population of the latter would favor hierarchical galaxy formation scenarios (White & Frenk 1991), while the former would support early formation of galaxies through monolithic collapse (Larson 1975). Therefore, the study of ERGs can help to constrain existing models of the formation and evolution of galaxies.

The observed very red colors of those ERGs that are classified as elliptical galaxies are attributed predominantly to the large $K$-correction arising from their high redshift. On the other hand, star-forming galaxies will owe their redness predominantly to dust extinction. This view implies that extremely red elliptical galaxies will occur only at high redshift ($z \approx 1$) while ERGs at $z \approx 1$ will exhibit unusually heavy obscuration of either stellar or active galactic nucleus (AGN) emission, or both. This is expected to be the reason for the small space density found for ERGs in the local universe.

This Letter reports the discovery of an ERG, PDF J011423, at $z = 0.65$. Multiwavelength photometric and spectroscopic observations reveal evidence of both star formation and AGN activity in this galaxy, which can be regarded as a "local" template for the study of this class of ERG at higher redshifts. Throughout this Letter, we adopt $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$.

2. OBSERVATIONS

PDF J011423 ($\alpha = 01^h14^m23^s$, $\delta = -45^\circ34'30''$, J2000) was first noted as a faint 1.4 GHz radio source ($S_{1.4GHz} = 1.67$ mJy) in the Phoenix Deep Survey (Hopkins et al. 1998, 1999). Aperture photometry of the optical counterpart of the source gives $R = 21.1$ and $V = 22.7$ (Georgakakis et al. 1999), locating PDF J011423 close to the magnitude limit of the follow-up Two Degree Field multifiber spectroscopic survey (Georgakakis et al. 1999). Nevertheless, a strong emission line, identified as [O ii] $\lambda 3727$ at a redshift $z = 0.65$, was detected.

In the light of the known strong correlation between the far-infrared and 1.4 GHz luminosities for star-forming galaxies, these clues were sufficient to schedule PDF J011423 for observation by the Infrared Space Observatory (ISO), using ISOCAM (7 and 15 $\mu$m) and ISOPHOT (90 $\mu$m). The ISO observations (J. Afonso et al. 2001, in preparation) revealed the presence of a relatively bright source at 7 and 15 $\mu$m, with fluxes of 4.1 and 7.6 mJy, respectively. The object was also detected by ISO at 90 $\mu$m (4 $\sigma$ level), with a flux of 260 mJy. Subsequent near-IR photometry, using the New Technology Telescope (NTT) and the Cerro Tololo Inter-American Observatory 1.5 m telescopes, showed this galaxy to have $K = 15.3$ and $J = 18.4$. PDF J011423 is thus classified as an ERG with $R-K = 5.8$ and $J-K = 3.1$.

The closeness and the relatively bright optical magnitude of PDF J011423 allows detailed spectroscopy of this object at both...
optical and near-IR wavelengths. The optical spectroscopic observations were obtained at the Very Large Telescope (VLT) using the FOcal Reducer/low dispersion Spectrograph 1 (FORS1) instrument in long-slit mode. Three dithered observations of 15 minutes each were made using a 1.6′ wide slit and a low-resolution grism (150I), covering the wavelength range λ0.6–1.1 μm. Bias subtraction, flat-fielding, and the combination of the dithered observations were performed before extracting the final spectrum using the software package IRAF. The wavelength scale was defined by fitting a third-order polynomial to the lines of an He-Ar calibration spectrum. The spectrum of the standard star GD 50 was taken for the flux calibration, which agrees with the optical photometry of PDF J011423 within 15%. Near-IR spectroscopy was obtained using the Son of Isaac (SOFI) instrument on the ESO NTT. Twelve observations of 270 s each, dithered along a 170′ slit, were obtained. The low-resolution grism covering the range λ0.95–1.64 μm was used. The dithered observations were flat-fielded and combined before the spectrum was extracted. For the wavelength calibration, a Xe lamp spectrum was used. The photometric calibration was performed using the J-band magnitude of the galaxy. The final calibrated spectra are presented in Figure 1 with the respective line measurements, based on Gaussian fits to the emission lines, given in Table 1.

### Table 1: Line Measurements for PDF J011423

| Line          | λ_{obs} (Å) | F_{obs} (×10^{-16} ergs s^{-1} cm^{-2}) | W_{rest} (Å) |
|---------------|-------------|----------------------------------------|--------------|
| [O ii] 3726, 3729 | 6159 ± 1    | 8.0 ± 0.3                              | 90 ± 6       |
| Hβ           | 8033 ± 4    | 1.0 ± 0.2                              | 10 ± 4       |
| [O iii] λ4959 | 8195 ± 4    | 2.0 ± 0.8                              | 19 ± 11      |
| [O iii] λ5007 | 8274 ± 4    | 3.7 ± 0.7                              | 32 ± 10      |
| Hα + [N ii]  | 10858 ± 11  | 28.7 ± 2.5                             | 217 ± 47     |

*Measurements from a single Gaussian fit to the observed blend.*
linked (e.g., Rowan-Robinson 1995), here we simply superpose the SEDs predicted by the two models.

The model fit, presented in Figure 2, results from a $\chi^2$ minimization to the observed SED, varying within the domain of the parameters of the original starburst and AGN models. The more powerful component, responsible for 76% of the infrared luminosity ($L_{\text{1-1000}\mu m}$), is a model of a dusty starburst of age 57 Myr, with optical opacities of the GMCs in the range $\tau_v = 3-200$. The properties of this component are determined primarily by the constraints imposed by the far-IR and optical emission.

The starburst component alone is, however, unable to fit the mid-IR data. Therefore, an extra contribution in the form of emission from hot dust (7 ~ 160–1600 K) heated by a putative AGN is required. This component represents 24% of the total infrared luminosity. Acceptable fits could also be obtained using other AGN models, for example, by allowing for emission from a dusty torus surrounding the central (black hole) source (Efstathiou, Hough, & Young 1995). Both classes of models lead to similar descriptions of the object in the context of this Letter.

The best-fit model SED in Figure 2 predicts an infrared luminosity of $L_{\text{1-1000}\mu m} = 7.1 \times 10^{12} \, h_\odot^{-2} \, L_\odot$, which classifies PDF J011423 as an ultraluminous infrared galaxy (ULIRG). The possibility that the high luminosity is due to gravitational lensing is unlikely, given the relatively low redshift of the object.

The existence of only one data point in the far-IR/submillimeter part of the SED makes an estimate of the dust mass for PDF J011423 highly uncertain. However, the fitted SED in this wavelength range is compatible with an optically thin thermal dust emission spectrum (emissivity index of 1.5) with a temperature of $T_{\text{dust}} = 33 \pm 3$ K, which corresponds to a dust mass of $M_{\text{dust}} \sim (8-30) \times 10^8 \, h_\odot^{-2} \, M_\odot$ (Hildebrand 1983). Consistent with the extreme reddening of the galaxy, this value is an order of magnitude higher than the dust mass of $10^7-10^8 \, h_\odot^{-2} \, M_\odot$ found for local ULIRGs (Sanders & Mirabel 1996) and comparable to the higher values found in the sample of Palomar Green quasars of Haas et al. (2000), for example.

The two models used to fit the observed SED do not predict the radio continuum luminosity or spectral index. To interpret the radio data, we appeal to the remarkably tight empirical correlation between the far-IR and radio continuum luminosity observed in star-forming galaxies (Helou, Soifer, & Rowan-Robinson 1985; Condon 1992). The favored explanation of the correlation holds that the same massive stars warm the far-IR to the unresolved contribution of $[N\text{II}]$ blend. This excess over the SFR estimated from far-IR dust extinction of $A_v \approx 5-6$ mag. This large extinction is likely to be the source of the extreme red color in PDF J011423. The absence of the 4000 Å break in the optical spectrum, indicating an optical continuum dominated by very young stars, is consistent with the inference that this is a vigorously star-forming galaxy. The measured optical line widths are not significantly larger than the instrumental resolution, placing an upper limit of approximately 500 $\text{km s}^{-1}$ on their intrinsic value.

In the near-IR spectrum, the H$\alpha$ + [N II] blend presents a width value of $FWHM \sim 2000 \, \text{km s}^{-1}$ (after correction for instrumental resolution). Given the low resolution of the spectrum, it is not clear if this shows an intrinsic broad-line component for H$\alpha$ or is due to significant contribution from [N II].

The diagnostic line ratios (Rola, Terlevich, & Terlevich 1997; Veilleux & Osterbrock 1987) for PDF J011423, after correction for dust obscuration, are consistent with the two-component model. While ratios involving the [O II] $\lambda 3727$ line ([O II] $\lambda 3727$/H$\beta = 8.0$) indicate excitation by an AGN, the other line ratios ([O III] $\lambda 5007$/H$\beta = 2.9$, [S II]/H$\alpha = 0.2-0.3$) and the nondetection of [O I] $\lambda 6300$ are indicative of a starburst. This kind of ambiguous spectral line classification has been linked previously to galaxies composite in nature, i.e., hosting both a starburst and an AGN (Hill et al. 1999).

The presence of an AGN in addition to the starburst component complicates the estimation of the star formation rate (SFR). The most reliable measure is from its 60 $\mu$m luminosity $(2.4 \times 10^{26} \, h_\odot^{-2} \, W \, \text{Hz}^{-1})$, where the model implies that the dominant contribution is due to the starburst. Using the appropriate calibration (Cram et al. 1998) for an initial mass function of the form $\Psi(M) \sim M^{-2.5}$ with stellar masses between 0.1 and 100 $M_\odot$, we estimate a SFR for massive stars of SFR$_{60\mu m}(M \geq 5 \, M_\odot) = 470 \, h_\odot^{-2} \, M_\odot \, \text{yr}^{-1}$. Alternatively, from the observed radio power ($P_{1.4 \, \text{GHz}} = 1.5 \times 10^{24} \, h_\odot^{-2} \, W \, \text{Hz}^{-1}$), we deduce SFR$_{1.4 \, \text{GHz}}(M \geq 5 \, M_\odot) = 377 \, h_\odot^{-2} \, M_\odot \, \text{yr}^{-1}$, consistent with the value estimated from the 60 $\mu$m luminosity. On the other hand, the extinction-corrected H$\alpha$ luminosity [$L_{\text{H}\alpha} = (0.9-2.6) \times 10^{37} \, h_\odot^{-2} \, W]$ implies SFR$_{\text{H}\alpha}(M \geq 5 \, M_\odot) = 620-1730 \, h_\odot^{-2} \, M_\odot \, \text{yr}^{-1}$, the large range being due to the unresolved contribution of [N II] to the observed H$\alpha$ + [N II] blend. This excess over the SFR estimated from far-IR and radio luminosities may be due to the AGN contribution.

Three other dusty ERGs have been spectroscopically confirmed and are relatively well studied: HR 10, displaying strong starburst activity at $z = 1.44$ (Dey et al. 1999); ISO J1324–2016, a $z = 1.50$ galaxy that hosts a dusty quasar (Pierre et al. 2001); and ERO J164023, which at $z = 1.05$ shows star-forming activity with a possible weak AGN (Smith et al. 2001). A brief comparison of some of the observed quantities in PDF J011423 and these three other dusty ERGs is listed in Table 2. Although the nondetection of star formation...
in ISO J1324−2016 can be due to the lack of far-IR/submillimeter observations, it seems clear that different degrees of AGN and starburst activity do exist in the dusty ERG population. Given the lower redshift of PDF J011423, this source offers the best opportunity to study the interplay between the two phenomena in the dusty environments of these galaxies.

The ratio of the radio power to the dust-corrected optical luminosity of PDF J011423, \( P_{\text{r}}/L_{\text{B}} \sim 1 \), confirms that PDF J011423 is radio-quiet. It seems likely that this source is linked to the radio-quiet counterparts of the red quasar population discovered by Webster et al. (1995) and also to the ERGs recently discovered among the population responsible for the hard X-ray background (Hasinger et al. 2001). Future work will show if the intense star formation activity present in PDF J011423 is also a common feature to the above-mentioned obscured AGN populations.

All these different studies suggest the existence of an important population of dusty ERGs, powered by heavily obscured starbursts and/or AGNs, which is now starting to be observed. Given the extreme nature of the dusty ERGs, their study will hold fundamental clues to the understanding of galaxy evolution, by revealing valuable information on the hidden star formation and AGN activity in the universe.

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