Faint Infrared-Excess Field Galaxies: FROGS

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Abstract. Deep near-infrared and optical imaging surveys in the field reveal a curious population of galaxies that are infrared-bright \((I-K \gtrsim 4)\), yet with relatively blue optical colors \((V-I \lesssim 2)\). Their surface density, several per square arcminute at \(K > 20\), is high enough that if placed at \(z > 1\) as our models suggest, their space densities are about one-tenth of \(\phi_\ast\). The colors of these “faint red outlier galaxies” (FROGS) may derive from exceedingly old underlying stellar populations, a dust-embedded starburst or AGN, or a combination thereof. Determining the nature of these FROGS has implications for our understanding of the processes that give rise to infrared-excess galaxies in general. We report on an ongoing study of several targets with HST & Keck imaging and Keck/LRIS multislit spectroscopy.

1. Introduction

Infrared-bright galaxies have been found both locally (e.g. Arp 220 & IRAS ultraluminous-infrared galaxies) and at high redshifts \((z \gtrsim 1)\) in field and cluster-search surveys (e.g. Francis et al. 1997; Spinrad et al. 1997). The first deep field infrared surveys by Elston et al. (1988 & 1989) and more recent ones (Songaila et al. 1994; Glazebrook et al. 1995; Moustakas et al. 1997) have all revealed small numbers of very faint galaxies with dramatic optical–near-infrared colors. Many of these are also red in their optical–optical colors, and are consistent with being passively evolving ellipticals at \(z \sim 1\). However, there is also a curious population of faint \((I \gtrsim 24)\) galaxies that are infrared-bright \((I-K \gtrsim 4)\), yet with relatively blue optical colors \((V-I \lesssim 2.5)\); see Figure 9 of Moustakas et al. 1997). The colors of these “faint red outlier galaxies” (FROGS) may derive from exceedingly old underlying stellar populations, a dust-embedded starburst or AGN, or a combination thereof. In either case, the dramatic \(I-K\) color strongly implies that the 4000Å break lies between the \(I\)- and \(K\)-bands, which implies that \(1 < z < 4.3\). Models strongly suggest that they are actually at \(1 \lesssim z \lesssim 3\). This redshift range falls between \(z < 1\) redshift-survey and the \(z \gtrsim 3\) galaxies being routinely discovered now (Steidel et al. 1996). Our goal is to find what connections FROGS and “extremely red objects” (EROS; \(R-K > 6; I-K \sim 6.5\)) have between each other and with the observed galaxy types at both

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high- and low-redshift ends. Therefore, we have undertaken an observational and modeling program to characterize the nature of the FROGS, on whose progress we report here.

2. Observations

As the FROGs’ colors and morphology are relatively nondescript in the optical, identifying targets requires both deep optical and near-infrared imaging. Our original sample was drawn from deep ground-based NTT (optical) and Keck (near-infrared) data (Moustakas et al. 1997). More recently, we have studied candidates in the HDF (Figure 1) using public and archival data, and especially in the deep “Westphal” pointing of the Groth Survey Strip (the “dGSS”; Figure 2) using the archival WFPC2 data as a starting point. With candidates identified in the latter field, we have obtained high-resolution near-infrared imaging with NICMOS (F160W on NIC2) and have (as yet unsuccessfully; see Table 1) attempted to obtain redshifts using multislit spectroscopy with Keck/LRIS.

Figure 1. The four FROG candidates in the Hubble Deep Field (F814W), identified using the optical WFPC2 photometry and the deep K-band imaging of Hogg et al. (1997). Their optical morphologies are disturbed, suggesting that they are not relaxed, uniformly old systems. Their near-infrared (HST/NICMOS) morphologies, and especially spectroscopy, are necessary follow-up observations to help determine the nature of the underlying stellar populations and their dust content.

Table 1. Summary of Observations in the dGSS Field (Moustakas et al., in prep.)

| Date  | Telescope | Instrument | Setting | Exposure | Seeing | Remarks          |
|-------|-----------|------------|---------|----------|--------|------------------|
| 94 Mar| HST       | WFPC2      | F814W   | 23,100s  | ~0.15" | Westphal GO-5109 |
| 94 Mar| HST       | WFPC2      | F606W   | 24,400s  | ~0.14" | Westphal GO-5109 |
| 96 Apr| Keck      | NIRCam     | K (2.2 μm) | 4,000s  | ~0.5"  | Excellent Conditions |
| 97 May| Keck      | LRISm      | 300 mm^-1 | ~8h     | ~0.7"  | Unphotometric    |
| 97 Sep| HST       | NICMOS     | F160W   | 12,031s  | ~0.2"  | Moustakas GO-7400 |

3. The Nature of the Faint Red Outlier Galaxies

The HST-determined optical and near-infrared FROG morphologies (Figures 1 & 2) are compact (~0.6") and asymmetric, suggesting that they are not relaxed
systems; and that the infrared “excess” is likely primarily due to dust. In that case, the nuclear region must be very (infrared-) bright relative to the (blue-ish) “disk,” and may be so either because of a nuclear starburst or an AGN (see e.g. Francis et al. 1996). Spectroscopic redshifts and features are necessary for further detailed study.

It is worth emphasizing that fROGS are selected in the field, and not in the vicinity of known quasars or AGN. Most of the EROS are in such fields (Hu & Ridgway 1994; Soifer et al. 1994; Graham & Dey 1996). Establishing the relation(s) between the several flavors of infrared-excess galaxies will be very important for understanding both the ages of high-redshift galaxies (e.g. Spinrad et al. 1997; Dunlop et al. 1996), the role dust plays as a function of redshift, and perhaps the frequency of AGN activity in galaxies at high redshift.

Figure 2. A frog candidate in the Westphal pointing of the Groth Survey Strip. The optical F606W and F814W HST/WFPC2 data were retrieved from the archive (AR #7524); the F160W HST/NICMOS image is from recently completed observations under the Guest Observer program #7460 (Moustakas et al.); and the deep K-band (2.2 µm) image is a portion of a large, deep mosaic in the dGSS, acquired in 1996 April at the Keck I Telescope with NIRC. An (underway) study of fROGS’ optical & near-infrared morphologies and surface-brightness profiles will help distinguish between age and dust as the causes of the infrared-excess light.

3.1. Motivation for Dusty & Disky Morphologies

The relative paucity of detections in Lyα-protogalaxy searches and mm observations of high-z galaxies show that dust is very important even at the earliest times. Spheroid formation may be triggered by mergers, which generate a central concentration of gas, which in turn induces a central starburst. This remains reddened by the produced dust, even if the gas is driven out by winds and shocks. At a later time, a disk forms by gas infall. This scenario (see e.g. Wang & Silk 1994) predicts that early on an early-type galaxy may appear as a dusty, evolved nucleus, surrounded by a young (blue) disk. This composite produces

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1However, at least one survey, the CADIS K′ Survey of Beckwith et al. (this conference) has produced several EROS in untargetted fields.
the correct FROG colors, assuming $\sim 1$ mag of extinction in the $K$-band in the nuclear regions.

4. Conclusions

The FROGs are likely very dusty, $z > 1.2$, systems, with a bright nucleus which is powered either by a (low-level) AGN or a starburst. They make up an appreciable fraction of faint infrared-selected samples ($\lesssim 10\%$ of all galaxies at $K \sim 20 - 22$), and so may represent a significant epoch or stage in the history of galaxy evolution. They are more numerous (by $\sim 10\times$) than EROS, although their colors are less extreme. Recently-obtained HST/NICMOS observations yield near-infrared morphological information, which combined with archival HST/WFPC2 images will provide clues for the origin of the “excess” infrared flux. Spectroscopic redshifts for these very faint galaxies have so far proven elusive, even with a dedicated effort with Keck. This will be an ideal project to pursue with next-generation ground- and space-based instrumentation, particularly NIRSPEC on Keck and SIRTF from space.

Acknowledgments. We thank the Organizing Committee for a very productive meeting. LAM particularly thanks the STScI for travel and attendance support through Program GO-7460.

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