PREDICTIONS FOR THE COUNTS OF FAINT, HIGH-REDSHIFT GALAXIES IN THE MID-INFRARED

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ABSTRACT

Deep mid-infrared (MIR) observations could reveal a population of faint, high-redshift (z > 3), dusty starburst galaxies that are the progenitors of present-day spheroids or bulges and are beyond the reach of current instruments. We utilize a semianalytic galaxy formation scheme to find a range of models for the MIR galaxy counts, down to a flux level of a few nanojanskys. The models incorporate the formation of heavily dust-enshrouded stellar populations at high redshift and are consistent with existing observations, including faint counts at 1.6 μm in the NICMOS Hubble Deep Field, and the upper limit on the extragalactic MIR background from TeV gamma rays. Our models predict ~0.04–0.4 galaxies arcsec⁻² at the threshold of 100 nJy at 6 μm, with a comparable or larger surface density at longer MIR wavelengths. We conclude that a significant new population of high-redshift galaxies could be detected by the James Webb Space Telescope. Such a population would constitute background noise for the Terrestrial Planet Finder (TPF) and could necessitate repeat observations: every TPF resolution element would have a chance of up to ~10% of being contaminated by a background galaxy.

Subject headings: cosmology: theory — early universe — galaxies: formation — galaxies: high-redshift — galaxies: ISM — infrared: galaxies — cosmology: theory — early universe — galaxies: formation — galaxies: high-redshift — galaxies: ISM — infrared: galaxies

1. INTRODUCTION

The past few years have seen significant progress in probing the ultra–high redshift universe, with both galaxies (Dey et al. 1998; Weymann et al. 1998; Spinrad et al. 1998; Hu, McMahon, & Cowie 1999; Ellis et al. 2001; Rhoads & Malhotra 2001; Malhotra & Rhoads 2002; Hu et al. 2002) and quasars (Fan et al. 1999, 2000; Zheng et al. 2000; Stern et al. 2000) being discovered in increasing numbers well beyond redshift z = 5. In hierarchical structure formation scenarios in cold dark matter (CDM) cosmologies, the first baryonic objects appear at still higher redshifts: at z ≈ 20–30, when the first high-σ peaks collapse near the Jeans scale of ~10⁶ M☉. (Haiman, Thoul, & Loeb 1996; see Barkana & Loeb 2001 for a recent review). Radiative cooling is efficient in the dense gas that has collapsed on these scales, and in principle, it can facilitate efficient star formation. Indeed, significant activity must have taken place at high redshifts in order to reionize the intergalactic medium (IGM) by z ≥ 6 and enrich it with metals by z ≥ 4 (see, e.g., Haiman 2003 and references therein).

The deepest detections of galaxies and quasars to date have been obtained at optical or near-infrared (NIR) wavelengths, where the objects were identified in broadband filters by their continuum, or in narrowband imaging observations by their Lyα emission. The James Webb Space Telescope (JWST) will be able to extend these observations to z ≥ 32 mag in the 1–5 μm wavelength range and detect minigalaxies and miniquasars at redshifts z ≥ 10. The expected number of faint sources in future deep NIR observations have been studied extensively in the context of hierarchical structure formation, using simple semianalytic models. Haiman & Loeb (1997, 1998) showed that if halos collapsing at high redshifts have reasonable star (or quasar black hole) formation efficiencies, they can then be detected in the NIR continuum in great numbers, with surface densities possibly reaching ~1000 sources arcmin⁻². Similarly large numbers of high-redshift objects could be detected through optical/NIR narrowband filters or spectroscopic imaging. The counts have been computed and found to be potentially significant for Lyα emission originating from either a usual stellar population (Haiman & Spaans 1999) or the release of gravitational binding energy (Haiman, Spaans, & Quataert 2000). In addition, recombination lines of helium fall into the optical/NIR, allowing the detection of high-redshift sources, provided they have sufficiently hard spectra (Tumlinson & Shull 2000; Oh, Haiman, & Rees 2001).

Observations at nearby redshifts have revealed that spheroid systems—the bulges of disk galaxies, as well as dwarf spheroidal galaxies—have exceedingly old stellar populations (see, e.g., Binney & Tremaine 1987). It is natural to assume that these objects formed at high redshifts. At the epoch when the halos harboring these objects first assembled, gas supply was likely plentiful, resulting in high star formation rates. In analogy with local starburst galaxies, these high-redshift bursts of star formation were likely heavily dust-enshrouded, with unusually red spectra enhancing fluxes at longer wavelengths. In this paper, our goal is to quantify this scenario and to predict the counts of faint, high-redshift galaxies at MIR wavelengths.

Semianalytic galaxy formation models, originally applied at optical wavelengths (Kauffmann & White 1993) have recently been extended to the far-infrared (FIR) and all the way to submillimeter range (Granato et al. 2000). The key to such extensions is the availability of template spectra that incorporate the absorption and reemission of starlight by dust. Dusty galaxy models have successfully matched spectra of known starburst galaxies (Gordon, Calzetti, & Witt 1997; Efstathiou, Rowan-Robinson, & Siebenmorgen 2000), as well as a broader range of galaxy types (Silva et al. 1998; Devriendt, Guiderdoni, & Sadat 1999). When combined with hierarchical galaxy formation schemes, such spectral models have also successfully reproduced the
existing IR/submillimeter luminosity functions (Guiderdoni et al. 1998; Silva et al. 2001) and have been used to investigate several aspects of IR galaxies, such as the faint-end slope of their luminosity function, and the abundance of ultraluminous infrared galaxies (ULIRGs; Devriendt & Guiderdoni 2000). IR counts have also been modeled outside the context of hierarchical structure formation models (for a recent review, see Rowan-Robinson 2001), using complementary, empirically based approaches (e.g., Pearson & Rowan-Robinson 1996; Malkan & Stecker 2001; Pearson 2001; Xu et al. 1998, 2001).

In the present paper, we consider the number counts of faint, high-redshift sources at MIR wavelengths, using similar semianalytic models. The main difference between the present paper and previous studies is that we extrapolate the models down to a very faint flux level. Our study is motivated primarily by the forthcoming instruments JWST, the Space Infrared Telescope Facility (SIRTF), and the Terrestrial Planet Finder (TPF). It is likely that JWST will have very deep (∼100 nJy) imaging capability in the MIR out to λ ∼ 30 μm.3 In very long exposure (∼10⁶ s) observations, SIRTF could, in principle, reach similar limiting fluxes, but it will be confusion-limited at much brighter levels. Roughly 100 nJy is also the target flux level for the IR version of TPF to discover Earth-like planets at a distance of 10 pc.

Observations in the MIR have only been possible in a few narrow bands from the ground, and the deepest existing surveys from space, i.e., by the Infrared Space Observatory (ISO), are still relatively shallow, achieving completeness only down to ∼0.1 mJy (see, e.g., Elbaz et al. 1999, 2002; Serjeant et al. 2000; and Franceschini 2003 for a review and further references). We use the models to obtain counts to the much fainter flux levels of ∼1 nJy. We emphasize that this is a very significant extrapolation from current data, by several orders of magnitude. Such extrapolations are inevitably uncertain. In this paper, we present two different models, one we consider “reasonable,” and a second model, which is more “extreme” (in the sense that it maximizes the MIR counts down to ∼100 nJy), but is (1) consistent with all existing observations and (2) not obviously physically unrealistic. While the former model is subject to large uncertainties, the latter model will serve as a robust guide to the most optimistic scenario for detecting ultrafaint galaxies with JWST, SIRTF, and TPF. In addition, these calculations will be useful to assess whether these observations may reach the MIR confusion limit.

The rest of this paper is organized as follows. In § 2, we describe the ingredients of our modeling, including the presence of dust, and discuss the relevant observational constraints. In § 3, we present the counts at different MIR wavelengths, describe the properties of the faint sources, such as typical masses and redshift distributions, and discuss the confusion limit. Finally, in § 4, we summarize our conclusions and the implications of this work. Throughout this paper, we assume a flat ΛCDM cosmology with the parameters (Ω_m, Ω_L, Ω_bh², h, σ_8h⁻¹) = (0.3, 0.7, 0.019, 0.7, 0.9).

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3 See instrument description at http://www.stsci.edu/nustar/instruments/miri and G. Serabyn et al. (1999), A Mid-Infrared Camera for the Next Generation Space Telescope, at http://ngst.gsfc.nasa.gov/publicdocs.html.
resulting in a sharp drop of flux at short wavelengths. Nearly all of the starlight at $\lambda \lesssim 5 \mu m$ is absorbed by dust in molecular clouds and reemitted at long wavelengths, until the star-forming clouds disperse and the dust opacity is significantly reduced (at $t \gtrsim 10$). At late times, as the dust is dispersed from the star-forming clouds, the spectrum evolves to be significantly bluer.

2.3. Calibration of Star Formation Efficiency and Existing Constraints

The final ingredient of our model is the calibration of the star formation efficiency in the dark halos. Although this could vary significantly from galaxy to galaxy, for simplicity we assume here that all halos of a given velocity dispersion turn the same amount of gas into stars. There are several approaches to choosing a calibration. When fitting existing data, such as galaxy counts, then the efficiencies can be chosen to be the best-fitting values (see, e.g., Kauffmann & White 1993). In the models of Haiman & Loeb (1997, 1998) that extrapolate to high redshifts, the star formation efficiency was normalized based on the mean metallicity of the high-redshift Ly$\alpha$ forest.

In the present work, we regard the overall normalization of the star formation efficiency as a free parameter, and we consider two different values, corresponding to a “reasonable” and a more “extreme” extrapolation (see also discussion below). We envision that the remnants of the high-redshift starbursts can be identified with the spheroid components in local galaxies. Accordingly, based on the Faber-Jackson relation, we adopt the scaling $M_{\star} \propto \sigma_{\text{halo}}^2$, where $M_{\star}$ is the mass turned into stars, and $\sigma_{\text{halo}}$ is the velocity dispersion of the host halo. We then normalize the models as follows:

$$\left( \frac{\sigma_{\text{halo}}}{115 \text{ km s}^{-1}} \right)^4 \left( \frac{M_{\star}}{1.5 \times 10^{10} M_{\odot}} \right) =$$

in the reasonable model and

$$\left( \frac{\sigma_{\text{halo}}}{115 \text{ km s}^{-1}} \right)^4 \left( \frac{M_{\star}}{1.5 \times 10^{11} M_{\odot}} \right) =$$

in the extreme model. In addition, we postulate that no stars form in halos with velocity dispersions less than 30 km s$^{-1}$, because of the presence of the UV background (see, e.g., Navarro & Steinmetz 1997). Prior to reionization (which we here assume to occur at redshift $z = 10$), we lower this threshold to 11.7 km s$^{-1}$, corresponding to a virial temperature of $10^4$ K, at which this cutoff is determined by the requirement of efficient cooling, rather than the feedback from the UV background (see, e.g., Haiman, Abel, & Rees 2000). We also note that equation (2) is still within reasonable agreement with the normalization of the Faber-Jackson relation derived for the bulges of local spiral galaxies (Whitmore, Kirshner, & Schechter 1979).

Using the standard relation between halo velocity dispersion and mass (see, e.g., Navarro, Frenk, & White 1997) and assuming that the gas available for star formation is $M_{\text{gas}} = (\Omega_{b}/\Omega_{m}) M_{\text{halo}}$, the stellar mass here corresponds nominally to $M_{\star}$ $\approx 2 M_{\text{gas}}$ (for the typical halos at each observed flux). Hence, our maximal model is rather extreme, in that it assumes the formation of several generations of massive stars, formed in quick succession, to use all

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4 Downloadable directly from http://grana.pd.astro.it.
the available gas for star formation at least twice (for reference, we note that the models in Haiman & Loeb (1997) had the much lower overall star formation efficiencies of $M_{\text{star}}/M_{\text{gas}} = 0.02 - 0.2$).

A stellar population with a Salpeter initial mass function (IMF) returns $\approx 30\%$ of its mass to the interstellar medium in $\approx 3 \times 10^8$ yr (we obtain this value by adopting the IMF slope of 2.35 between 0.1 and 125 $M_\odot$ and assuming that each star with mass above $\geq 2 M_\odot$ returns all of its mass, except for a 0.5 $M_\odot$ core, to the interstellar medium). This would allow recycling of the gas effectively only $1 + 0.3 + 0.09 + \ldots = 1.4$ times. The requirement in our extreme model could be achieved either with a flatter IMF (we find that an IMF slope of 2.05 instead of 2.35 is required for each generation to return $\approx 50\%$ of the mass) or by postulating a larger gas reservoir for a system with a given velocity version. Note that significant metal enrichment, to solar levels, implies that about 8 generations of star formation did indeed take place in the Milky Way (see, e.g., § 8.2 of Binney & Tremaine 1987, where in their “one zone” model each generation has a metallicity yield of $\frac{1}{3}$ of the solar value), and observed heavy-element abundances in galaxy clusters also favor significant enrichment at high redshifts (Renzini 1997).

Existing MIR counts (from ISOCAM) extend down only to about $\approx 0.1$ mJy (Elbaz et al. 1999, 2002; Serjeant et al. 2000; Franceschini et al. 2003; Franceschini et al. 1997; Clements et al. 1999), and we extrapolate the models to several orders of magnitude fainter flux levels. It is reassuring that in our extreme model, the integral counts at 6 and 15 $\mu$m are in good agreement with the observed value of $\approx 10^4$ deg$^{-2}$ (see, e.g., Elbaz et al. 1999). We note that our predictions are also similar to those in recent models by Franceschini et al. (2001), with counts of $\approx 4 \times 10^4$ deg$^{-2}$ at 1 $\mu$m at 24 $\mu$m.

Nevertheless, our normalization also needs to be consistent with faint galaxy counts in the Hubble Deep Field (HDF) in both optical and NIR bands. In particular, we found that the most constraining HDF data are the 1.6 $\mu$m galaxy counts in a NICMOS follow-up observation of $\approx 0.4$ of the HDF area (Thompson et al. 1999). This deep survey has a 50% completion limit near 28th magnitude and has detected a total of $\approx 300$ sources. We have found that models with the template spectra described in § 2.2 that are consistent with this abundance always satisfy the limits from optical/UV counts in the HDF to about the same depth. In Figure 2, we show the 1.6 $\mu$m counts in our models, with the extreme normalization in equation (2). The upper curve shows all sources, the lower curve shows only the sources beyond redshift $z = 5$, and the points show the NICMOS data. The figure explicitly demonstrates that our model is marginally consistent with the NICMOS counts.

An integral constraint on the MIR counts can also be obtained from the upper limit on the total cosmic infrared background energy density. The latter limit derives from the TeV gamma-ray spectrum of the blazar Mrk 501, observed in its high state with HEGRA, yielding a stringent limit on the optical depth to pair production at TeV energies (Stanev & Franceschini 1998; Dwek & de Jager 2000). The upper

Fig. 1.—Time-evolving template spectra adopted for our model dusty starburst galaxies. The spectra are obtained using GRASIL, a computer code by Silva et al. (1998).
In this section, we present the galaxy counts at different MIR wavelengths, describe the properties of the faint sources, such as typical masses and redshift distributions, and discuss the confusion limit for TPF.

3.1. Mid-Infrared Galaxy Counts

Figure 3 shows the cumulative galaxy counts at 6 \( \mu m \) in our extreme model. The upper solid curve shows all galaxies, and the lower curve shows only those beyond redshift \( z = 5 \). The dashed curve shows the contribution of the sources to the upper limit on the 6 \( \mu m \) background, as discussed above.

The most striking feature in Figure 3 is the large number of galaxies. At the flux threshold of 100 nJy, over 1000 sources are predicted per arcmin\(^2\). The flattening of the counts between \( \sim 30 \) and \( \sim 40 \) nJy is due to the lower limit we imposed on the velocity dispersion of halos that are able to host galaxies. It is worth emphasizing again that the deepest data from ISO only reach the comparatively shallow flux threshold of \( \sim 0.1 \) mJy (at 6.7 and 15 \( \mu m \)). In fact, the ISO counts (at 15 \( \mu m \)) appear to show a significant flating from 1 to \( \sim 0.1 \) mJy. This, however, is not inconsistent with a significant resteepling of the counts at fainter fluxes, revealing a new population, as predicted by our models.

This new population of faint, dusty, high-redshift galaxies is unlikely to be uncovered by SIRTF: although reaching the flux level of 100 nJy for a signal-to-noise ratio (S/N) = 5 detection of a point source is possible in an integration time of several times 10\(^5\) s (Simpson & Eisenhardt 1999), the confusion limit will be reached at much higher fluxes. JWST will be able to reach a similar sensitivity in \( \sim 10^4 \) s out to \( \sim 10 \) \( \mu m \) and in \( \sim 10^6 \) s out to \( \sim 30 \) \( \mu m \), while a “JWST Deep Field” with a 10\(^6\) s exposure could reach fluxes as faint as a few nanojanskys out to \( \sim 10 \) \( \mu m \). The flux threshold of 100 nJy has also been chosen as the target flux for the MIR version of TPF, based on its mission goal to detect Earth-like planets at a distance of 10 pc.\(^5\)

The characteristic properties of the sources making up the counts in Figures 2 and 3 are summarized by the four panels of Figure 4. In the top left panel, we illustrate the redshift distribution of the sources as a function of their 6 \( \mu m \) flux, by showing the redshifts at each flux beyond which sources make up a fraction 25\%, 50\%, and 100\% of the observed counts. The low-redshift cutoff is a result of the limit we imposed on the circular velocities of halos harboring active galaxies. The redshift distribution for fainter sources is clearly biased to higher redshifts, with an apparent upturn in the typical redshift below \( \sim 100 \) nJy. While approximately a half of the 100 nJy sources are located at \( z > 3 \), all of the 1 nJy sources are at \( z > 10 \). In the top right panel, we show the mass of gas that has been converted to stars in the halos at the 50\% redshift cut, together with the masses of their host halos. This explicitly demonstrates the

\(^{5}\) See http://sirtf.caltech.edu, http://www.ngst.nasa.gov, and http://tpf.jpl.nasa.gov for quantitative discussions of the sensitivities.
high star formation rates in our models, using up a nominal amount of gas up to ∼ half of the halo mass—implying multiple generations of star formation. The bottom left panel shows the ages of the sources at the 50% redshift cut. These are between $10^8$ and $10^9$ yr, with the fainter sources systematically younger. Finally, the bottom right panel shows the rarity of the density peaks hosting the halos at the 50% redshift cut, in units of the rms primordial density fluctuation $\sigma_m$. The typical sources correspond to 2–3 $\sigma_m$ peaks in the primordial density field.

In Figure 5, we show the cumulative galaxy counts at longer wavelengths, using our maximal, high star formation efficiency model (eq. [2]). The counts at 6, 15, and 30 μm are shown in Figure 5 for all sources (upper set of curves) and for sources located beyond redshift $z = 8$ (lower set of curves). Although the faint (∼100 nJy) 15 and 30 μm counts are somewhat below those at 6 μm, the 30 and 6 μm counts are comparable around 10 μJy. This follows directly from the dip in the spectra near 15 μm (see Fig. 1). For the highest redshift sources, the advantage of going to longer wavelengths is increased, with nearly an order of magnitude more sources at the 100 nJy threshold at 30 μm than at 6 μm. A considerable number of $z > 8$ galaxies, ∼15 arcmin$^{-2}$, are detectable at 30 μm at 100 nJy. In Figure 6, we show the cumulative galaxy counts at longer wavelengths, as in Figure 5, but using instead our reasonable star formation efficiency model (eq. [1]). Not surprisingly, the counts at fluxes of $\gtrsim 100$ nJy are ∼10 times lower than in the extreme model of Figure 5, reflecting the 10-fold reduction in our assumed star formation efficiency. Note, however, that at the very faint end, $\lesssim 10$ nJy, the reduction in the counts is less pronounced. This is because, at these faint fluxes, a significant fraction of the halos are below the critical value for star formation in the extreme model, but most halos corresponding
to these fluxes are still above the critical mass in the reasonable model.

3.2. Confusion Noise

The potentially large number of detectable sources raises the important question of confusion. For an instrument whose angular resolution elements have an effective solid angle $\Delta\Omega$, one can define the confusion limit such that a source at this flux corresponds to (say) a $3\sigma$ fluctuation of the unresolved background due to all fainter sources. The critical surface density of background sources according to this definition depends on the slope of the counts (see, e.g., eq. [8.26] in Franceschini 2003). The slope we find in the flux range $\sim 10^{-10} - 10^4$ nJy is close to $d\log N/d\log F \approx -1$ (see Figs. 3 and 5), implying that confusion limits set in at the surface density of one source per $\sim 9$ beams.

For the MIR version of $TPF$, the effective beam size is $0.25$ arcsec$^2$, and hence this instrument would be confusion-limited at the source surface density of $\sim 0.4$ arcsec$^{-2}$. This limit is shown as the dotted line in Figure 3. Although $TPF$ is an interferometer with high resolution and exquisite nulling, the beam size reflects the total collecting area of the side lobes and is relatively large.$^6$

For reference, we note that the effective size for the resolution element on $SIRTF$ at $\sim 8\mu m$ is $1.4$ arcsec$^2$ (Simpson & Eisenhardt 1999), and our models would predict a confusion limit of $\sim 1\mu Jy$ (in rough agreement with, although somewhat higher than, the estimate by Simpson & Eisenhardt 1999 of $0.5\mu Jy$, based on the extrapolated model number counts of Franceschini et al. 1991). At $24\mu m$, the $SIRTF$ confusion limit is about $10^4$ counts deg$^{-2}$ (assuming one source per 27 beams; Franceschini et al. 2001). Although we did not extend our models to sufficiently bright fluxes (to above $10\mu Jy$), extrapolating the counts shown in Figure 5 toward the bright end would reach this source density at around $0.1\mu Jy$, consistent with the findings of Franceschini et al. (2001). For $JWST$, the size of the resolution element in the wavelength range $\sim 1-3.5\mu m$ is much smaller, $0.0025$ arcsec$^2$ (see Gillett & Mountain 1998), and the predicted counts at shorter wavelengths are also somewhat lower than at MIR; based on Figure 2, we do not expect source confusion to be a problem down to $1\mu Jy$. At the longer wavelength of $24\mu m$, $JWST$ has a confusion limit of $5 \times 10^5$ counts deg$^{-2}$ (assuming one source per 27 beams and a 6 m mirror; Franceschini et al. 2001), which is reached in our models at around $200\mu Jy$.

As can be seen from Figures 3 and 5, the critical surface density of $\sim 0.4$ arcsec$^{-2}$ for $TPF$ is reached near $\sim 100\mu Jy$, i.e., close to the requisite target flux to detect Earth-like planets at 10 pc. High-redshift galaxies can cause other problems for $TPF$. The surface density of galaxies at the confusion limit implies that in 1 out of 10 pointings, a galaxy with $F_\nu \sim 100\mu Jy$ may be detected within the $TPF$ beam. Every detected planet can therefore have up to a $10\%$ chance of being a misidentified galaxy. Whether this is a significant contamination will, of course, depend on the rate at which planets are discovered by $TPF$. The unresolved background could also require greater $u$-$v$ plane coverage to obtain an unambiguous image. We emphasize that none of these problems is likely to be showstoppers for $TPF$: even for the maximum allowed surface density, repeat observations can be used to eliminate confusion-related problems.

4. CONCLUSIONS

Deep MIR observations of the universe could reveal a new population of ultrafaint, high-redshift ($z > 3$), dusty starburst galaxies that are the progenitors of present-day spheroids or bulges. Although at a flux level of $\sim 100\mu Jy$ these sources are beyond the reach of current instruments, the new population could be uncovered by $JWST$, and it could also constitute background noise for $TPF$. We used a simplified semianalytic galaxy formation scheme to quantify the MIR galaxy counts in an extreme model, designed to maximize the number of detectable sources down to a few nJy while being consistent with various existing constraints. The model incorporates the formation of heavily dust-shrouded stellar populations at high redshift.

Our results show that a new population could turn up at a flux level of $\sim 100\mu Jy$. The sources would have typical halo masses of $\sim 10^{11}$ $M_\odot$ (corresponding to $\sim 2\sigma$ peaks of the density field), redshifts $z > 3$ (with a significant tail at $z > 8$), and ages $\sim 3 \times 10^8$ yr. The models predict $0.04-0.4$ galaxies arcsec$^{-2}$ at the threshold of $100\mu Jy$ at $6\mu m$, with comparable or larger surface densities at longer MIR wavelengths, especially at the highest redshifts. These results indicate that high-redshift galaxies could potentially necessitate repeat observations with $TPF$. The discovery of these faint sources would be a unique and direct probe of the earliest galaxies, and a combination of several wavelengths should provide insight into their formation mechanism.

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$^6$ See the $TPF$ Handbook at http://tpf.jpl.nasa.gov/library/tpf_book/index.html.
