INFRARED SURVEYS: A GOLDEN AGE OF EXPLORATION

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1. Introduction

The next decade promises an explosion of information about the infrared sky from wavelengths from 1 μm to 1,000 μm, in the continuum and in spectral lines. Measurements of objects ranging from comets in the Kuiper Belt to newly-forming galaxies will be useful for almost every branch of astrophysics. The number of catalogued infrared sources will increase a thousand-fold from the 600,000 presently known from IRAS. This talk addresses the compelling scientific interest of the infrared and describes why, years from now, astronomers will view this decade as a golden era for the exploration of the infrared sky.

1.1. FUNDAMENTAL ASTROPHYSICS MOTIVATES INFRARED SURVEYS

Fundamental physical and astrophysical reasons have encouraged astronomers to target infrared wavelengths for many of the surveys planned for the next decade:

- Infrared surveys are almost immune to absorption by interstellar dust. The extinction in the K band (2.2 μm) is almost a factor of ten less, in magnitudes, than that in the V-band, and still less at longer wavelengths. The lack of dust extinction makes astrophysically important, but optically obscured regions such as protostars and the nuclei of active galaxies accessible, enables a complete census of objects in the Galactic Plane, and makes possible an unbiased count of external galaxies almost down to the Galactic Plane.
- Low mass stars of spectral types K and M comprise the dominant form of (known) baryonic mass in galaxies. Since the photospheric emission from these stars peaks in the near-IR, infrared surveys of galaxies trace

B.J. McLean et al. (eds.), New Horizons from Multi-Wavelength Sky Surveys, 27–40.

the stellar mass distribution directly whereas visible light observations trace hotter, younger stars that may show a different, more irregular distribution. Further, if a significant fraction of the "missing" mass of galaxies is in brown dwarf stars, then the emission from these objects peaks in the infrared as well.

- The interstellar medium (ISM) is prominent in mid and far-IR wavelengths. Dust grains absorb starlight and re-radiate the energy at wavelengths ranging from a few microns in the most energetic sources to longward of 1 mm. In addition to emitting a broad continuum, interstellar dust shows numerous spectral features that are indicative of grain composition and physical conditions. The IR is also rich in vibrational-rotational and fine structure lines of many elements, molecules, and ions. The study of these lines, some of which are the dominant cooling transitions for entire galaxies, offers important information on physical conditions within a wide variety of astronomical sources.
- Finally, the expansion of the Universe inexorably red-shifts the energy of the early Universe into the infrared. The visible and ultraviolet light of hot young stars (0.1–1 μm) and the spectral lines associated with star-forming regions or active galactic nuclei (AGN) move into the near-IR for an objects with redshifts of 5–10. The infrared emission associated with star-bursts itself suffers significant redshift in distant objects. The energy associated with star formation is emitted around 100 μm at zero redshift; hence dusty, primeval objects may only be found at wavelengths between 300–1,000 μm.

1.2. ADVANCED TECHNOLOGY ENABLES NEW SURVEYS

The factors of thousand(s) of improvement in survey depth and spatial resolution that are possible now relative to earlier surveys are due to three technological revolutions:

- The first IR surveys such as the Two Micron Sky Survey (TMSS), the Air Force Geophysical Laboratory Survey (AFGL), and the Infrared Astronomical Survey (IRAS) were obtained using a small number (1–100) of detectors. New surveys such as the 2 Micron All-Sky Survey (2MASS; Skrutskie *et al.* 1996) and the various surveys planned for the Space Infrared Telescope Facility (SIRTF) will take advantage of arrays as large 256 × 256. These arrays offer background-limited performance even from space and provide thousands of pixels of information with a single exposure. Today's state-of-the art in infrared arrays ranges from 256 × 256 to 1024 × 1024 at 1–5 μm, 128 × 128 to 256 × 256 from 5–40

μm, and 32×32 for 40–120 μm. Only for wavelengths longer than 120 μm is the technology limited to arrays of fewer than 100 detectors.

- The ability to work from space with cold telescopes is critical to sensitivity in the infrared. Escaping the Earth's atmosphere allows two huge advantages: freedom from atmospheric obscuration that otherwise limits observations to a few translucent windows; and reduced thermal background that results in observations to a given sensitivity on similarly-sized telescopes being a million-times faster from space than from the ground. A number of satellites have demonstrated the advantages of space-borne IR telescopes, including: IRAS, the Cosmic Background Explorer (COBE), the Infrared Space Observatory (ISO), and the Japanese Infrared Telescope in Space (IRTS).
- Finally, advances in high performance computing are critical to large scale surveys. All-sky surveys like 2MASS and its European counterpart DENIS produce up to 20 GByte of data per day and over 10 Terabytes during a complete survey. Powerful workstations with inexpensive disks and millions of floating point operations per second are a *sine qua non.* Disseminating the results of these surveys efficiently will take advantage of the ever-expanding global networks.

2. Overview of Infrared Surveys

2.1. A SURVEY FIGURE OF MERIT

With all these technological advances, the infrared is now approaching the all-sky sensitivity already achieved at other wavelengths. Figure 1 shows survey detection limits over the complete electromagnetic spectrum, from the radio to gamma-rays. A few, very-deep pencil beam surveys from ISO, HST, and SIRTF are also shown. Table 1 lists the properties of some past, on-going, or planned surveys. While the radio and optical surveys (particularly the Sloan Digital Sky Survey (SDSS)) lead other wavelength bands in overall sensitivity, the infrared is catching up.

Of particular interest is the volume that a particular survey explores. This figure of merit tells how well a particular survey can both find rare objects and detect large numbers of objects of various classes to determine their spatial distribution and other statistical properties. The survey volume is proportional to the survey solid angle and, in Euclidean space, to the cube of limiting distance. Since the limiting distance is proportional to the square root of the limiting flux density, we can write:

$$Relative\,Volume = \frac{\Omega}{\Omega(IRAS)}\left(\frac{\nu F_\nu}{\nu F_\nu(IRAS)}\right)^{-1.5}$$

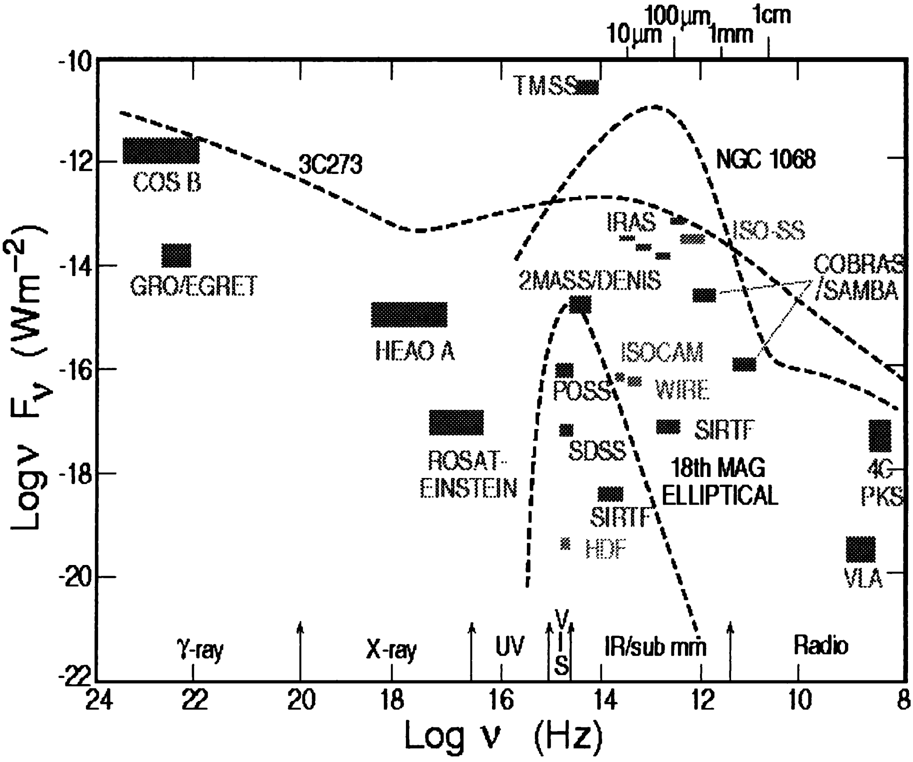

Figure 1. A comparison of surveys across the entire electro-magnetic spectrum shows the greatest sensitivity in energy per logarithmic interval (νF_ν) has been achieved in the optical and radio. Surveys plotted include: the VLA First radio survey, the planned COBRAS/SAMBA all-sky survey in the submillimeter, the various IRAS bands from the Faint Source Survey, the Wide-Field Infrared Explorer(WIRE), the 2MASS and DENIS surveys in the near-IR, the original Two Micron Sky Survey (TMSS), the Palomar Observatory Sky Survey (POSS) and the Sloan Digital Sky Survey (SDSS) in the visible, the ROSAT and Einstein Surveys in the X-ray region, and the EGRET survey from the Gamma Ray Observatory. A few very deep surveys with small solid angle coverage are shown in grey, *e.g.*, the ISO Serendipity Survey, the Hubble Deep Field and its potential NICMOS follow-up, various ISO and SIRTF deep surveys.

where we have normalized the volume relative to the ~96% sky coverage of the IRAS Survey.

Examination of Table 1 shows that the Sloan Digital Sky Survey (SDSS) will probe the largest volume of space at the high-energy end of the infrared (0.7–0.9 μm). However, the 2MASS and DENIS surveys, SIRTF, the Wide-Field Infrared Explorer (WIRE; Shupe *et al.*, this volume, p. 118), and ESA's recently selected COBRAS/SAMBA mission will all explore important wavelength bands with great sensitivity.

TABLE 1. **Selected Infrared Point Source Surveys**

Survey Name	Wavelength (μm)	Sensitivity (mJy)	Area (sq.deg.)	Relative Volume (FSC-60=1)
SDSS	0.7	0.0018	10,300	1.7×10^4
COBRAS/SAMBA	350	20	41,250	650
SIRTF	3	0.0014	2	42
2MASS	2.2	1	41,250	29
2MASS/DENIS	1.25	1	41,250	12.4
WIRE	25	1	400	11
HST-NICMOS	1.6	3×10^{-5}	2.5×10^{-3}	6.9
DENIS	2.2	2	20,600	5.1
IRAS PSC/FSC	60	250	39,600	1.0
SIRTF	70	0.5	2	0.6
IRAS PSC/FSC	25	200	39,600	0.38
IRAS PSC	100	1,000	39,600	0.27
IRAS FSC	12	150	39,600	0.19
ISO-CAM Parallel	6.7	1	33	0.12
ISO-PHOT Serendipity	180	2,000	4,125	0.024
ISO-CAM Deep	15	0.3	1	0.08
ISO-CAM Deep	6.7	0.05	0.2	0.07

2.2. GROUND-BASED NEAR-IR SURVEYS

Two near-IR sky surveys are presently underway. The 2MASS survey will start in mid-1997 to survey the entire sky to sensitivity limits of 15.8, 15.1, and 14.3 mag at wavelengths of 1.25 (J), 1.65 (H) and 2.2 μm (K_s). The European DENIS project is already surveying the Southern sky at I, J and K down to comparable limits. These surveys will detect ~300–500 million stars ($K<14.3$ mag) and 1 million galaxies ($K< 13.5$ mag) and should be complete by the year 2000. One of the important aspects of the near-IR surveys is that a long wavelength baseline is necessary to identify interesting objects in these vast source catalogs. The near-IR colors of most objects cover only a small range of values. The addition of one or more optical bands (from simultaneous I-band measurements for DENIS and from POSS-I, POSS-II or SDSS for 2MASS) breaks this degeneracy, enabling the identification of interesting galaxies, quasars, and late type stars (Figure 2). Association of near-IR sources with optical, radio, and X-ray identifications will be straight-forward with the $< 1''$ positional accuracy of these catalogs. Detection of proper motions relative to POSS I will give a 40–50 year baseline to identify nearby stars.

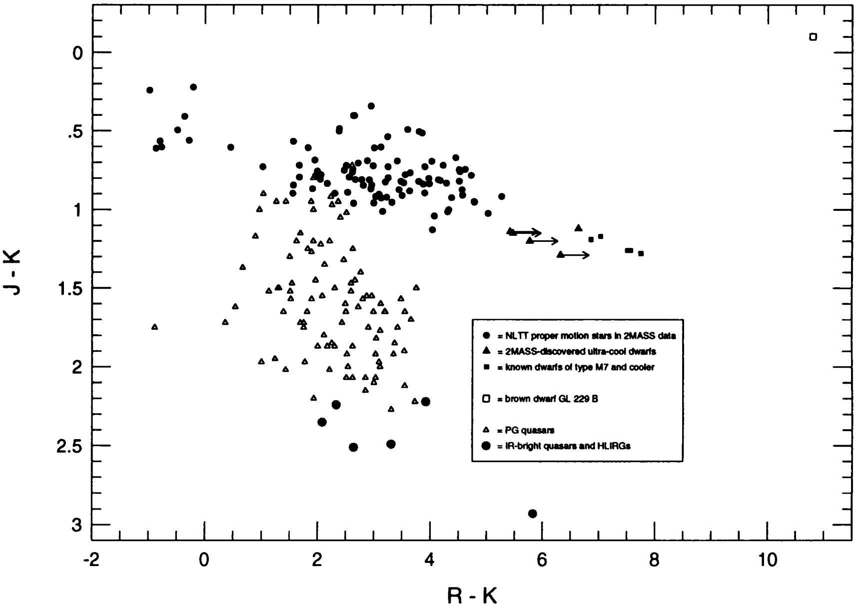

Figure 2. A optical-near-IR color-color diagram shows a wide variety of astronomical objects can be identified through their colors.

2.3. SPECTROSCOPIC SURVEYS FOLLOW SPATIAL SURVEYS

Once an initial reconnaissance has been carried out in a new wavelength, spectroscopic surveys become important to characterize the nature of particular objects and to study the physical conditions in the diffuse medium. The infrared is only now obtaining these critical data. The IRAS-Low Resolution Spectrometer measured the brightest ~5,000 stars from 7 to 18 μm. The COBE Far Infrared Spectrometer (FIRAS) made all-sky spectral maps at low spectral and spatial resolution and measured the global properties of a few key spectral lines in the ISM of our Galaxy, *e.g.*, [CII] at 157 μm and [NII] at 205 μm (Wright *et al.* 1991). But the greatest step forward in this area is taking place now with the flight of ISO. Perhaps the greatest legacy from ISO will be spectra obtained with its Short and Long Wavelength Spectrometers (SWS and LWS), the ISOPHOT-Spectrometer, and low spectral resolution images obtained with ISOCAM. Together these instruments provide unparalleled access to the 2 to 200 μm spectra of all types of astronomical objects at a variety of spatial (3″ to 3′) and spectral (R ~50 to 30,000) resolutions. These data are just becoming coming available, but the wealth of information is spectacular:

- Lines previously obscured by the Earth's atmosphere, such as thermally excited transitions of H_2O and H_2, as well as lines of condensed volatiles such as CO_2 and H_2O ices have been detected toward late type stars and embedded young stars.
- Maps have been made in various gas lines and dust features in regions showing a broad range of density and photon energy density. These maps will make possible realistic physical models of gas excitation, dust and chemical abundances in obscured regions.
- Fine-structure lines of elements, *e.g.*, Neon, at various ionization stages are extremely useful diagnostics of the density, temperature and exciting spectra. Because they can reach into highly obscured nuclei of galaxies, they are invaluable for addressing the nature of the power source, starburst or black hole, in those nuclei.

The Japanese IRTS mission systematically mapped about 10% of the sky at modest spectral resolution with a $8'$ beam and will complement ISO spectroscopy of specific sources. IRTS will provide spectra of thousands of stars and detailed information on the distribution of various gas phase species, PAHs and other grains throughout the ISM, *e.g.*, Onaka *et al.* (1996).

A number of future infrared missions will carry out spectroscopic surveys, including:

- The Submillimeter Wavelength Satellite (SWAS) will be launched in 1997 and will take ~500 GHz spectra in specific lines of H_2O, O_2, CO, and C, toward molecular clouds and galaxies to help understand the distribution of these fundamental species.
- SIRTF will take modest-resolution spectra of thousands of faint galactic and extra-galactic sources from 5 to 40 μm.
- SOFIA will obtain spectra with particular emphasis on high spectral resolution measurements in the submillimeter.
- FIRST will provide complete spectral coverage of selected areas with 1 km s^{-1} resolution for $100 > \lambda > 800$ μm.

3. Representative Science Projects for Next Generation Surveys

Some of the most important questions in astrophysics will be addressed by the spatial and spectral surveys, planned or now underway. The following list is hardly exhaustive, but represents the breadth of science possible with surveys expected within the next decade.

3.1. THE LOW-MASS END OF THE MAIN SEQUENCE

One of the first uses of the near-IR surveys will be to determine the shape of the low-mass portion of the stellar luminosity function and to search for isolated brown dwarf stars. It is difficult to answer these questions in the optical due to the faintness and redness of these stars, and to the uncertain conversion from magnitude to mass. Existing visible data on the lowest mass stars are ambiguous and stars of low mass could still account for a significant amount of the mass in the solar neighborhood (Mera *et al.* 1996).

Data from the 2MASS prototype camera have already increased the number of stars known to be later than M8 by 30% and identified the lowest mass field star, >M10.5V (Kirkpatrick *et al.* 1996). Figure 3 shows the numbers of M dwarf stars that might be expected in the 2MASS survey. It is interesting to note that the one brown dwarf detected to date, GL 229 B has the near-IR colors of an A0 star due to deep CH_4 absorption at 1.2 and 1.6 μm (Oppenheimer *et al.* 1996), but when the visible band color is added, the remarkable properties (R$-$K$\sim$ 10 mag!), of this object stand out in the upper right corner of Figure 2. The 2MASS magnitude limits correspond to distance limits of 5–10 pc for an object like GL 229 B. Assuming a flat mass function beyond the terminus of the main sequence we find that there might be as many as 600 brown dwarfs in the mass-range between 0.08 and 0.02 $M_\odot$ in the full-sky 2MASS survey.

The wavelength of peak emission from objects less massive or older than GL 229 B shifts further into the thermal infrared where sensitive observations are possible only from space. The 5–18 μm camera on ISO, ISOCAM, will search for brown dwarfs in a variety of environments, including:

- Targeted surveys in Ophiuchus and the Hyades to look for young, high luminosity objects.
- The Parallel Mode survey at 6.7 μm will examine $\sim$33 sq. deg. to 1 mJy (100 times deeper than IRAS) to look for field brown dwarfs.
- A shallow, wide-area survey will examine a few sq. deg. to 1 mJy
- A number of deep, high latitude surveys at 6.7 and 15 μm will look for very faint brown dwarfs over 0.2–1 sq. degree to 0.05–0.3 mJy.
- Deep maps of external galaxies will look for brown dwarf halos.

The ultimate mission to search for elusive field brown dwarfs will be the WIRE mission which will be launched in 1998. WIRE will cover 400 square degrees with the mJy sensitivity necessary to detect brown dwarfs over the entire mass-age plane. WIRE will either find field brown dwarfs or set a definitive limit to their local space density.

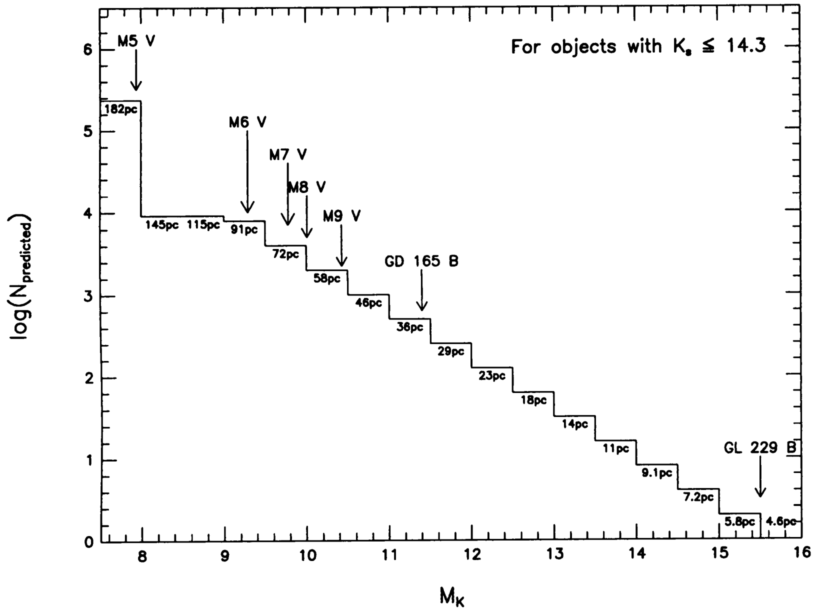

Figure 3. The number of M dwarf stars of different types expected in the 2MASS survey.

3.2. THE STRUCTURE OF THE GALAXY AND THE ISM

The Galactic plane beyond a distance of 1 kpc is almost completely obscured at visible wavelengths. Infrared studies from COBE and IRAS suggest that the Galaxy has a bar (Weinberg *et al.* 1992; Blitz and Spergel 1991). 2MASS and DENIS will find AGB stars (K_s<10 mag) across entire galaxy to test this assertion and to determine the horizontal and vertical scale lengths of many late-type stars. ISO and the infrared instrument on the Mid-Course Space Experiment (MSX; Price, this volume, p. 115) will make ~10 μm maps of selected areas of the plane with far higher spatial resolution and sensitivity than was possible with IRAS.

The large scale structure of the ISM has already been mapped by IRAS and COBE. Recently, all the 60 and 100 μm IRAS data within ±4° of the plane were processed with the High Resolution (HIRES) algorithm (Aumann *et al.* 1990; Cao *et al.* 1996) to reveal new structures in the dust emission. The IRAS HIRES maps have ~ 1′ resolution and can be compared directly with radio data in HI (from DRAO) and CO (from

FCRAO) lines to yield a complete picture of the energetics and kinematics of the gas (atomic and molecular) and the dust.

ISO has revealed the presence of compact regions within molecular clouds having $F_\nu(200\,\mu\mathrm{m}) > 50F_\nu(60\,\mu\mathrm{m}$ (Laureijs *et al.* 1996; Bogun *et al.* 1996). Complete spectral energy distributions of cloud cores from a combination of IRAS, ISO, and IRTS observations will be used to unravel the contributions of different dust populations and heating mechanisms. A complete survey of the cold component of the ISM must await the launch of the COBRAS/SAMBA satellite which will make all-sky maps with $5'$ resolution in the submillimeter.

3.3. THE STRUCTURE OF THE LOCAL UNIVERSE

Deep, near-IR pencil-beam surveys from ground-based telescopes have established the K luminosity function of galaxies to K~24 mag and have probed galaxy evolution at redshifts $z < 3$ (Cowie *et al.* 1994; Djorgovski *et al.* 1995). Small K-corrections and negligible effects of dust make conversion of source counts into a luminosity function straight-forward for comparison with evolutionary models. Although the effects of evolution do not appear to be as pronounced in the K counts as at optical wavelengths (Djorgovski *et al.* 1995), some evolution is required for an $\Omega \sim 1$ Universe.

Variations in the galaxy counts at the bright end (K<15 mag) are found in different parts of the sky, implying the existence of structures on the scale of 300 h^{-1} Mpc (Huang *et al.* 1996). Investigating these variations is a fundamental goal of the 2MASS and DENIS surveys. The near-IR surveys will be more uniform in their coverage of galaxy types than IRAS which was biased toward star-forming spirals. Preliminary analysis of 2MASS prototype camera data indicates that ellipticals and spirals are detected almost equally well out to redshifts of $z \sim 0.1$ (Figure 4).

3.4. A UNIFORM CENSUS OF QUASARS

The lack of a near-IR sky survey leaves unanswered important questions about quasars and other energetic objects: Is there a missing population of dust-embedded quasars that has been missed in optical surveys? Is there a missing link between IRAS ultra-luminous objects and UV-selected quasars? The broad range of optical-IR colors for radio-selected quasars suggests that up to $A_V \sim 5--10$ mag of dust might be present in a parent population of quasars and that only a small, un-extincted part of that population may have been found in optical searches (Webster *et al.* 1995). A number of authors have contested this view based on optical follow-up of red, radio-selected quasar-candidates (Wall; this volume, p. 191) and of X-ray selected quasars (Boyle and diMatteo 1995). These arguments

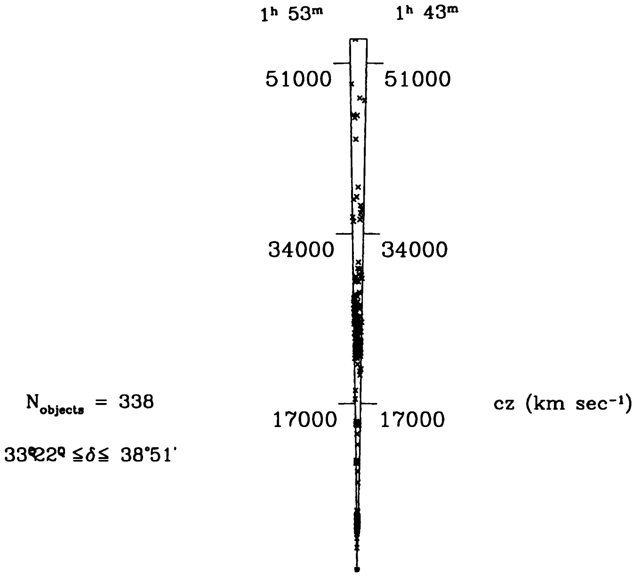

Figure 4. A pencil beam survey showing 2MASS galaxies detected with the prototype camera toward Abell 262. Galaxies are seen far beyond the cluster redshift of 3,000 km s^{-1} (Huchra and Schnieder, private communication).

are necessarily indirect and deep red-sensitive surveys such as SDSS and 2MASS are required for a definitive answer. Figure 5 (Beichman *et al.* 1997) shows how the surface density of a given population of quasars might vary at different wavelengths for different amounts of dust. Extrapolation of optical source counts to the near-IR using quasar colors (Elvis *et al.* 1994) suggests that 2MASS will find $\sim$ 0.3 quasar per sq. deg. at $K_s \sim 14.5$ mag in the absence of dust. Finding significantly more quasars than this value might imply that extinction has hidden a significant part of the true quasar population. Although optical surveys are biased even by small amounts of dust, the SDSS will be sufficiently sensitive over a broad enough area that it should find all but the most deeply reddened objects. The combination of these two surveys will unambiguously determine the population of nearby quasars.

There is as yet insufficient data from 2MASS or DENIS to determine the near-IR quasar density. However, the first 2MASS QSO has been identified through its red optical-IR colors. Optical follow-up of objects in a 0.15 sq. deg. region led to the discovery of a relatively nearby, low luminosity quasar at $z = 0.147$ (Beichman *et al.* 1997).

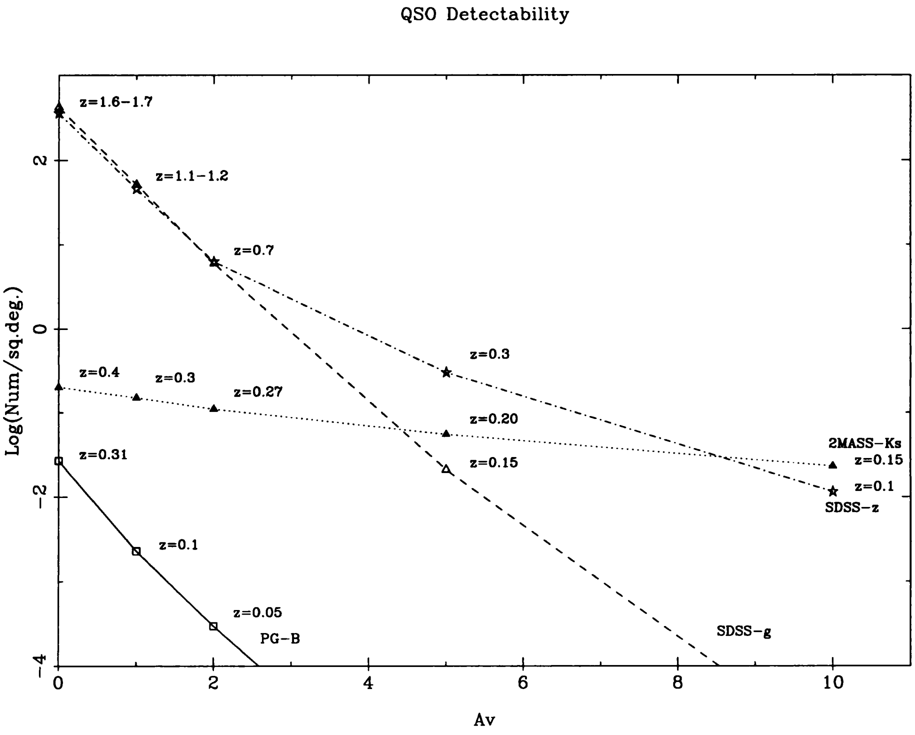

Figure 5. The surface density of quasars expected in different surveys as a function of internal quasar extinction. Surveys shown include 2 bands from the SDSS, 2MASS at K_s, and a representative blue survey with the POSS.

3.5. THE SEARCH FOR PROTO-GALAXIES

When did the first galaxies originate? Did galaxies form via collapse of larger objects, or through agglomeration of smaller clumps? The answers to these questions will be found through observations of objects at $z \sim 5$ and demand surveys in two separate IR wavelengths regimes:

- Observations in the near-IR to find the emission from redshifted UV-Optical light from young galaxies.
- Observations in the far-IR and sub-millimeter to find the emission from dust heated by UV-Optical light in young galaxies.

Which spectral region is most important depends on the unknown rate of dust formation in proto-galaxies. While the Hubble Deep Field (HDF) represents the first look at individual objects in the early Universe at $V \sim 30$ mag (!), objects at very high redshift will be much brighter in the near-IR than in the optical. It will be fascinating to see what the NICMOS observations of the HDF reveal when that instrument is launched early next year. At wavelengths longer than those probed by NICMOS, mid-IR surveys will look for starlight and very hot dust in young galaxies. ISOCAM surveys are presently underway at 6.7 and 15 μm, and WIRE surveys are planned at 12 and 25 μm, which will reach to $z \sim 1$. SIRTF surveys at 3–8 μm will be sensitive to L_* galaxies out to $z > 5$.

If dust plays a strong role in the appearance of proto-galaxies, then far-infrared and submillimeter observations are essential to study galaxy formation. Some interpretations of the COBE FIRAS data suggest the existence of a significant extra-galactic background (Abergel *et al.* 1996) due to distant, young galaxies. SIRTF will help resolve this question with 70 μm surveys planned to reach $\sim$ 1 mJy over a few sq. deg. The COBRAS/SAMBA mission will make a definitive all-sky survey to ~20 mJy at a number of far-IR and submm wavelengths. These space observations will be complemented by millimeter and sub-millimeter array telescopes on the ground which are also sensitive to the dust continuum emission from high redshift sources.

Acknowledgements

It is a pleasure to thank my 2MASS colleagues Mike Skrutskie, Tom Chester, Roc Cutri, Carol Lonsdale, John Huchra, Steve Schneider, and Will Pughe for discussions of 2MASS prototype camera results. I am indebted to Davy Kirkpatrick for his valuable insights into the properties of late type stars in the 2MASS data. George Helou and Martin Harwit graciously described some of the exciting new results from ISO.

This work was supported by IPAC which is operated by JPL and Caltech under contract with NASA.

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