THE ASTROPHYSICAL JOURNAL, 507:155–160, 1998 November 1

STAR FORMATION RATES IN FAINT RADIO GALAXIES

L. CRAM AND A. HOPKINS
School of Physics, University of Sydney, Sydney NSW 2006, Australia; L.Cram, A.Hopkins@physics.usyd.edu.au
AND
B. MOBASHER AND M. ROWAN-ROBINSON
Astrophysics Group, Imperial College, London SW6, England, UK; bm, mrr@ic.edu.uk
Received 1998 April 23; accepted 1998 June 8

ABSTRACT

The decimetric radio continuum luminosity of a star-forming galaxy appears to be directly proportional to the rate of formation of supernovae in the galaxy. Since decimetric radiation does not suffer significant extinction and is not directive, radio luminosities may thus provide a particularly straightforward way to determine the current rate of star formation. Using a sample of over 700 local galaxies, we confirm the utility of the radio luminosity as a measure of star formation rate by showing concordance with the rates predicted by U-band, Hα, and far-infrared luminosities. We also show that there are systematic discrepancies between these various indicators, suggesting that the Hα luminosity may underestimate the star formation rate by approximately an order of magnitude when the star formation rate is $\gtrsim 20\ M_\odot\ \mathrm{yr}^{-1}$. We use this calibration and the measured radio luminosities of sub-mJy radio sources to infer the star formation rate in approximately 60 star-forming galaxies at moderate ($z \gtrsim 0.1$) redshifts, both as the actual rate and as the fraction of the existing mass of stars in the galaxy. For some of these objects, the inferred current rate of star formation could increase the stellar mass in the galaxy by approximately 10% over an interval of ≈ 30 Myr.

Subject headings: galaxies: evolution — galaxies: starburst — galaxies: stellar content — radio continuum: galaxies

1. INTRODUCTION

In the vast majority of extragalactic radio sources with 1.4 GHz flux density $S_{1.4} \gtrsim 5$ mJy, the radio emission appears to be due to the existence of a nuclear "monster" or "engine." These sources are members of the class of powerful radio galaxies, emitting a spectral power density $P_{1.4} \gtrsim 10^{23}$ W Hz^{-1} (e.g., Condon 1989, especially his Fig. 12; Wall & Jackson 1997). Their optical hosts are intrinsically bright elliptical galaxies with optical luminosities of the order of 5×10^{37} W, often with red colors (e.g., Kron, Koo, & Windhorst 1985) and occasionally with high-excitation optical emission-line spectra (e.g., Hine & Longair 1979). While the nuclear monster may stimulate some nuclear star formation, or vice versa, there is not a tight relationship between the radio power and either the number of stars or the current rate of star formation in the host galaxy.

Many of the remaining extragalactic radio sources with $S_{1.4} \gtrsim 5$ mJy, as well as a large fraction of fainter sources, belong to a different population. These have optical counterparts that are spiral (if $V \lesssim 18.5$) or blue-peculiar (if $V \gtrsim 18.5$) galaxies with a wide range of optical luminosities, often displaying evidence of ongoing star formation (Kron et al. 1985; Benn et al. 1993). For the more luminous members of this population, it is known that there is a tight correlation between the far-infrared (FIR) luminosity and the 1.4 GHz radio power (reviewed by Condon 1992). Astrophysical interpretations of this correlation usually identify both the FIR and the radio emission as the consequence of ongoing massive star formation. As a corollary, the opportunity exists to determine the current rate of massive star formation from measurements of the FIR or radio luminosity.

The astrophysical significance of this opportunity is heightened by the fact that very deep radio surveys reveal large numbers of star-forming galaxies at redshifts well beyond $z \approx 0.1$, at an epoch where there is growing evidence that some classes of galaxies experience star formation at a rate higher than in the local universe. In this paper we explore the calibration of the relationship between radio luminosity and star formation rate (SFR) using a sample of local star-forming galaxies with measured radio flux densities, and then we apply the calibration to determine the current star formation rate in a sample of galaxies at $0.1 \lesssim z \lesssim 0.5$.

2. STAR FORMATION RATES

Several different measures have been used to estimate the current star formation rate in galaxies, including the far-UV or U-band magnitude, the strength of Balmer line emission, the power radiated in the FIR, and the radio luminosity (see, e.g., Gallagher & Hunter 1987; Ferrini 1997). Each indicator has been the subject of many previous investigations, but even so the complexity of the astrophysics underlying each one leads to a considerable degree of uncertainty in its use as an estimator of the star formation rate.

In this section we present a simple account of the physical basis of selected indicators and empirically check their utility using a sample of nearby galaxies for which the radio flux density and several other indicators are available. We have sought to base the comparison on similar physical assumptions, most notably by adopting similar initial mass functions (IMF), similar models for the time-dependence of the SFR, and similar models of stellar population evolution. The calibrations quoted below can be traced wherever possible to an IMF that varies as $\Psi(M) \sim M^{-2.5}$ between limits of 0.1 and 100 $M_\odot$ and to calculations based on the galaxy evolution models of Bruzual & Charlot (1993) and of

Fioc & Rocca-Volmerange (1997). Where necessary, scaling has been applied to accommodate different physical assumptions and to produce a homogeneous set of indicators. This scaling introduces potential uncertainties of about a factor of 2 between the ab initio calibration of the various indicators but could be adjusted if found to lead to inconsistencies.

Radio continuum emission at 1.4 GHz from star-forming galaxies is mainly synchrotron radiation produced by relativistic electrons. It has long been acknowledged that supernovae could play the dominant role in accelerating these electrons (Biermann 1976; Kirk 1994). This view has been reinforced by the discovery of the tight correlation between radio-continuum and FIR emission (reviewed by Condon 1992), indicating that massive stars may control both radiation mechanisms. The implication is that the supernova rate determines the nonthermal radio luminosity.

At first sight there is a serious problem with this interpretation, since the total radio luminosity of a galaxy divided by the typical luminosity of a supernova remnant implies supernova rates that are too high (Biermann 1976; Gehrz, Sramek, & Weedman 1983; Condon & Yin 1990). The problem can be resolved consistently with our understanding of supernova shock acceleration mechanisms by assuming that accelerated electrons, and perhaps the acceleration process itself, endure far longer than the $\sim 2 \times 10^4$ yr lifetime of detectable Galactic supernova remnants (Condon & Yin 1990). In this case the relationship between the radio luminosity and the supernova rate can be calibrated using the Galactic values of $L_{1.4} \sim 2.3 \times 10^{22}$ W Hz^{-1} and $\nu_{\rm SN} \sim 1/43$ yr^{-1}. From this, Condon (1992) estimates the SFR of stars massive enough to form the supernovae that contribute to radio emission (i.e., $M \geq 8\ M_{\odot}$), which can be adjusted using the above model for the IMF to yield

$$\mathrm{SFR}_{1.4}(M \geq 5\ M_{\odot}) = \frac{L_{1.4}}{4.0 \times 10^{21}\ \mathrm{W\ Hz^{-1}}}\ M_{\odot}\ \mathrm{yr}^{-1}\ . \quad (1)$$

Pérez-Olina & Colina (1995) present a theory of the relation between SFR and radio luminosity for extreme starbursts, which rests on the suggestion that the nonthermal emission from such galaxies may be dominated by radio supernovae with lifetimes of 100 yr or so, rather than remnants with lifetimes exceeding 20,000 yr. Their model predicts a SFR within a factor of ~ 2 of that given by equation (1), since the estimates involve a direct trade-off between the shorter duration but higher flux density of the emission from radio supernovae when compared with supernova remnants. This equivalence (and indeed the form of eq. [1]) requires that the SFR be constant over the lifetime of the least massive supernova progenitors ($\approx 10^{7.5}$ yr), and the estimate is based on a burst of star formation of this duration.

Balmer line emission from star-forming galaxies is formed in H II regions ionized by early-type stars. Kennicutt (1983a) has determined the theoretical relationship between the Hα luminosity and the current rate of star formation in a galaxy in a form corresponding to

$$\mathrm{SFR}_{\mathrm{H}\alpha}(M \geq 5\ M_{\odot}) = \frac{L(\mathrm{H}\alpha)}{1.5 \times 10^{34}\ \mathrm{W}}\ M_{\odot}\ \mathrm{yr}^{-1}\ . \quad (2)$$

An upward adjustment of 1.1 magnitude in the luminosity has been factored in to this equation to compensate for the mean extinction in Hα as suggested by Kennicutt (1983a), who also emphasizes that variations in extinction imply that *individual* measurements of Hα luminosity must be treated with caution. Kennicutt points out that the statistical properties of a sample will be considerably more accurate than measures of individual objects, a view supported by the robustness of the data shown in Figure 1 (see below).

FIR emission from star-forming regions is due to the absorption of stellar photospheric radiation by grains, with subsequent re-radiation as thermal continuum in the FIR. A simple theory relating the FIR power of a galaxy to its current massive SFR can be based on the proposition that

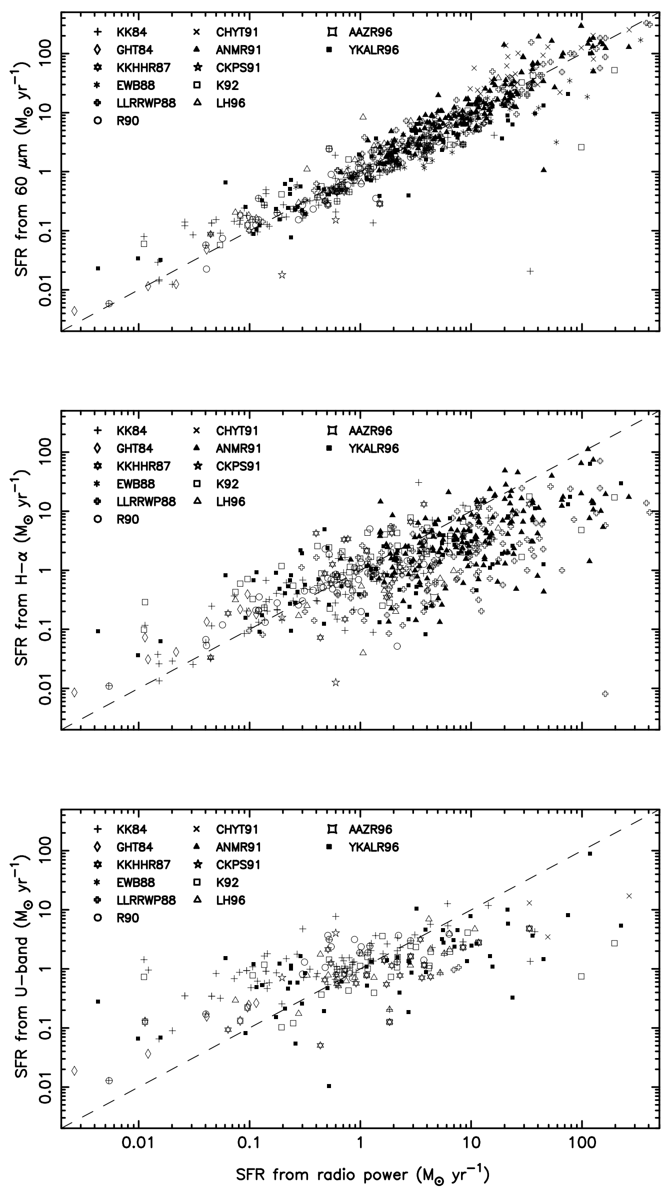

FIG. 1.—Comparison of SFRs deduced from 1.4 GHz luminosities (horizontal axis) with the rates deduced using the other luminosities indicated. Symbols are coded by the initials of the author's last names and the year of publication and cross-referenced in Table 1.

essentially all of the UV and much of the blue radiation from massive stars is absorbed by grains, with the associated thermal re-radiation appearing as emission in the 40–120 μm band (e.g., Xu 1990). From these ideas, Condon (1992) derives a SFR equivalent to

$$\mathrm{SFR}_{\mathrm{FIR}}(M \geq 5\ M_\odot) = \frac{L_{60\,\mu\mathrm{m}}}{5.1 \times 10^{23}\ \mathrm{W\ Hz^{-1}}}\ M_\odot\ \mathrm{yr}^{-1}\ . \tag{3}$$

Thronson & Telesco (1986) derive a rate that is $\sim$2.3 times larger than this. The difference is due to their inclusion of the effect of dispersal of the placental star-forming cloud and gives a fair indication of the unavoidable uncertainty in such theories. As noted by Bothun, Lonsdale, & Rice (1989), there is a "lingering ambiguity" concerning the relative importance of old disk stars and newly formed stars in heating grains in normal disk galaxies, and several authors (e.g., Lonsdale Persson & Helou 1987) have argued that radiation from stars less massive than 5 $M_\odot$ will contribute significantly to FIR emission from galactic disks. This casts doubt on the quantitative reliability of equation (3).

The use of far-UV or U-band luminosities to infer the current SFR rests on the idea that UV emission contains a substantial contribution of light from the photospheres of young, massive stars (e.g., Cowie et al. 1997). However, the calibration of a UV indicator is less straightforward than those listed above. Consider, for example, the evolution of the U-band luminosity following the sudden formation of 1 $M_\odot$ of stars with an IMF that varies as $M^{-2.5}$. The spectral synthesis models of Bruzual & Charlot (1993) and Fioc & Rocca-Volmerange (1997) predict that the U-band absolute magnitude brightens to $U \approx -0.7$ after $10^{6.5}$ yr and fades steadily thereafter, reaching $U \approx 1.7$ after $10^{7.5}$ yr. A starburst of $10^{7.5}$ yr would then lead to the relationship $\mathrm{SFR}_U(M > 5\ M_\odot) \approx L_U/1.4 \times 10^{21}\ M_\odot\ \mathrm{yr}^{-1}$. However, substitution of typical U-band luminosities of disk galaxies into this relation will give values of SFR that appear to be unreasonably high. The error is due to the large numbers of relatively old stars that also contribute to the actual U-band luminosity of disk galaxies. To avoid this problem, we have used the relationship between SFR and far-UV luminosity given by Cowie et al. (1997), scaled from 250 nm to the U-band using relevant synthesized spectra, to derive

$$\mathrm{SFR}_U(M \geq 5\ M_\odot) = \frac{L_U}{1.5 \times 10^{22}\ \mathrm{W\ Hz^{-1}}}\ M_\odot\ \mathrm{yr}^{-1}\ . \tag{4}$$

The model used by Cowie et al. (1997) assumes a steady rate of star formation over a long interval and is somewhat sensitive to the assumed history of star formation (see also Gallagher & Hunter 1987; Kennicutt, Tamblyn, & Congdon 1994). It has the great advantage of being directly related to one of the favored methods of determining the SFR in high-redshift ($z \gtrsim 1$) galaxies (Cowie et al. 1997).

An intercomparison of the rates predicted by equations (1)–(4) for a sample of local galaxies is illustrated in Figure 1, which plots the SFR deduced from Hα, FIR, and U-band luminosities against the SFR deduced from the 1.4 GHz luminosity. We have used 13 "reference" samples to test the relations as summarized in Table 1, which lists the sources of the data, the reference code used in Figure 1, and the number of galaxies from each source for which the designated SFR indicators have been located.

The data of Kennicutt & Kent (1983), Romanishin (1990), Kennicutt (1992), Lehnert & Heckman (1996), and Young et al. (1996) were chosen because these authors tabulate a relatively large number of galaxy-integrated Hα luminosities. Eales, Wynn-Williams, & Beichman (1988) and Condon, Anderson, & Helou (1991a) were chosen to give good coverage of the more luminous *IRAS* galaxies, albeit without Hα data, while Leech et al. (1988) and Allen et al. (1991) provide coverage of a broad range of *IRAS* galaxies. Gallagher, Hunter, & Tutukov (1984), Kennicutt et al. (1987), Caldwell et al. (1991), and Alonso-Herrero et al. (1996) cover smaller samples of galaxies of particular interest in studies of star formation.

The Hα equivalent widths or luminosities have been taken from the original papers. In an attempt to correct for any slit losses where the Hα data have been obtained spectroscopically, we have derived the equivalent width from the published Hα data and then used published optical aperture photometry to estimate the total Hα flux. Many Hα measurements include contamination from the nearby [N II] line, and where required we have multiplied the published flux by a factor of 0.75 to account for this effect

TABLE 1

SOURCES OF DATA

Authors	Code	Selection Criteria	Numbers of Galaxies: 1.4 GHz	Hα	60 μm	U-band
Kennicutt & Kent (1983)	KK83	Optical magnitude limited, mostly spirals	110	91	104	85
Gallagher et al. (1984)	GHT84	Irr/Spirals with high SFR	8	9	8	8
Kennicut et al. (1987)	KKHHR87	Interacting spirals	37	29	23	24
Eales et al. (1988)	EWB88	*IRAS* galaxies	59		59	
Leech et al. (1988)	LLRRWP88	Northern hemisphere *IRAS* galaxies	133	65	131	2
Romanishin (1990)	R90	Spirals	42	42	39	20
Condon et al. (1991a)	CHYT91	Ultra-luminous *IRAS* galaxies	32		32	4
Allen et al. (1991)	ANMR91	Southern hemisphere *IRAS* galaxies	179	179	179	
Caldwell et al. (1991)	CKPS91	Sa galaxies	1	1	1	1
Kennicutt (1992)	K92	Nearby, diverse types	55	50	47	40
Lehnert & Heckman (1996)	LH96	IR-selected starbursts (edge on)	28	13	27	19
Alonso-Herrero et al. (1996)	AAZR96	Hα-selected starbursts	2	2	1	
Young et al. (1996)	YKALR96	Galaxies with CO data	74	74	70	57
Benn et al. (1993)	...	VLA & WRST 1.4 GHz, deep surveys	39	39	...	...
Hopkins et al. (1998)	...	ATCA 1.4 GHz, deep survey	24	24	...	...

(Kennicutt 1992). The NASA Extragalactic Database (NED) has been consulted to obtain *U*-band magnitudes, most of the necessary redshifts, the *B*-band or *V*-band photometry used to convert Hα equivalent widths to flux densities, and the FIR flux density, when not already available in the original publication. If necessary, values of radio flux densities taken from the original papers have been converted to 1.4 GHz using a spectral index of $\alpha = +0.8 (S_\nu \propto \nu^{-\alpha})$. The on-line NRAO/VLA Sky Survey (NVSS) database (Condon et al. 1998) was used to obtain 1.4 GHz flux densities where they were not already published. A point is plotted in Figure 1 whenever a galaxy has a published radio luminosity and at least one other luminosity; we do not require that *all* SFR indicators be available before plotting a galaxy. Data for a galaxy in the original references has been plotted only if its 1.4 GHz flux density is available: the few radio-loud objects in the original references are also plotted in the appropriate diagrams. All measurements have been adjusted to correspond to a Hubble constant $H_0 = 75$ km s^{-1} Mpc^{-1}.

Figure 2 plots the radio/Hα data for two samples of *distant* star-forming galaxies, namely the objects classified as some variant of "$*$" in Table 3 of Benn et al. (1993) and the objects classified as "Type A" in the optical follow-up of the Phoenix survey (Hopkins et al. 1998; Hopkins 1998). These classifications, based on optical colors and the emission-line spectra, select the star-forming galaxies and reject the classical radio galaxies for which radio luminosity is not a measure of the SFR. There are obvious similarities between this plot and the corresponding radio/Hα plot for the nearby sample.

3. DISCUSSION

We first consider the "nearby" sample, in which several different estimators of SFR are often available for a single galaxy. Figure 1 indicates that SFR estimates based on the various indicators are in broad agreement with one another, but it also points to the existence of systematic differences between different estimators of the SFR. There are also several objects in which at least one indicator is significantly discordant.

The tightness of the relationship between the SFRs estimated from 1.4 GHz and 60 μm data reflects the well-studied radio/FIR correlation. Estimates of SFRs obtained from the two frequencies agree closely over more than 4 orders of magnitude. There is a tendency for objects with $\mathrm{SFR}_{1.4} < 0.2\ M_\odot\ \mathrm{yr}^{-1}$ to have relatively high values of $\mathrm{SFR}_{\mathrm{FIR}}$, perhaps revealing some heating due to the general interstellar radiation field of older disk stars, without associated supernovae due to younger massive stars (see also Lonsdale, Persson, & Helou 1987). A notable exception to the correlation is the very small number of galaxies in which the radio prediction is unusually high. These objects include NGC 4374 (M84; 3C 272.1) from Kennicutt & Kent (1983), IRAS 0421+040 from Eales et al. (1988), and Mrk 3 (4C+70.05) from Kennicutt (1992). In each case there was clear prior evidence that the radio emission is not related to star formation, and the objects have been retained in our data set only to illustrate the effect of "radio-loud" galaxies.

The existence of these objects points to the potential problem that 1.4 GHz luminosities may be "contaminated" by radio emission arising from a nuclear monster, rather than star formation. In deducing the SFR from radio flux densities, this contamination can be minimized by applying the following principles: (1) optical colors and optical spectral line ratios successfully delineate the class of objects with emission dominated by star formation (e.g., Benn et al. 1993), (2) the fraction of galaxies that owe their radio emission to star formation rises quickly with decreasing flux density in the sub-mJy radio source population (e.g., Kron et al. 1985; Wall & Jackson 1997), (3) any optical emission lines in classical radio galaxies with relatively low radio powers are relatively weak but lie in the high-excitation part of the relevant diagnostic diagram (e.g., Baum & Heckman 1989), and (4) the bimodal character of the radio-loud/radio-quiet dichotomy allows the use of the radio/optical flux density ratio to exclude the most powerful radio-loud objects (e.g., Sopp & Alexander 1991, their Fig. 1.)

Figure 1 shows that estimates of the SFR based on the widely used Hα luminosity indicator tend to be more scattered (relative to $\mathrm{SFR}_{1.4}$) than the $\mathrm{SFR}_{1.4}/\mathrm{SFR}_{\mathrm{FIR}}$ correlation. They also tend to lie about a factor of 10 above the trend defined by the 1.4 GHz/60 μm estimates when SFR $\lesssim 0.1\ M_\odot\ \mathrm{yr}^{-1}$, and about a factor of 10 below the trend when SFR $\gtrsim 20\ M_\odot\ \mathrm{yr}^{-1}$. The systematic deviations, which could have important implications for studies of the galaxy-

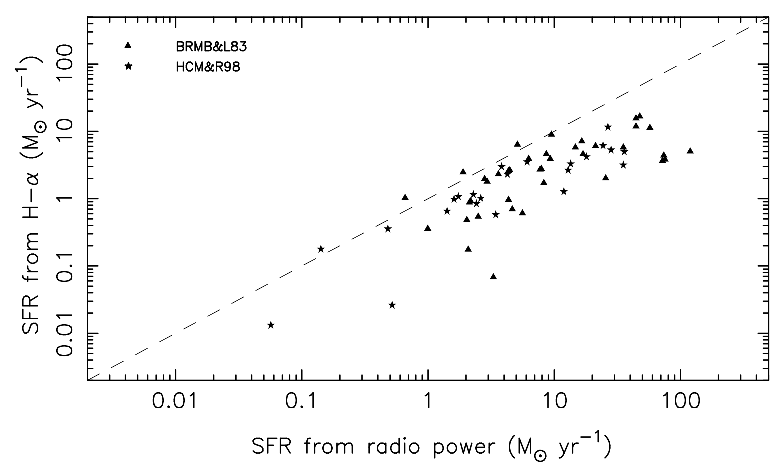

FIG. 2.—Comparison of SFRs deduced from 1.4 GHz luminosities (horizontal axis) with the rates deduced from measured Hα luminosities for two samples of faint radio galaxies. Triangles denote the sample of Benn et al. (1993), and stars denote the sample of Hopkins (1998) and Hopkins et al. (1998).

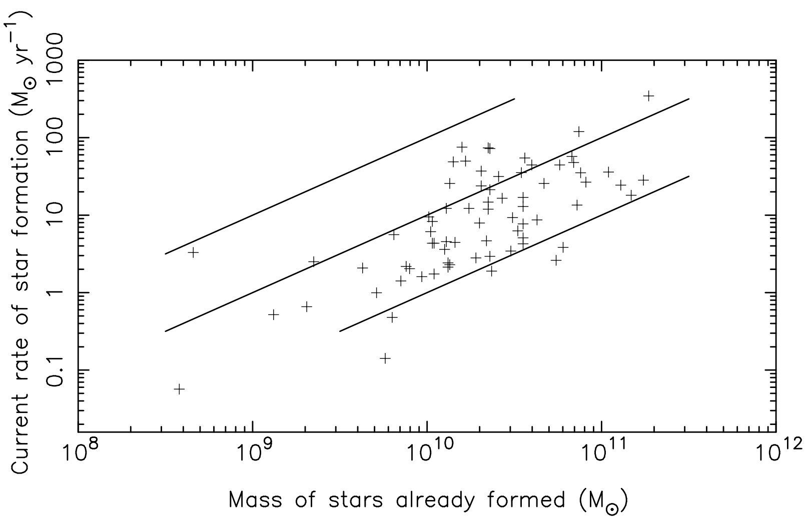

FIG. 3.—Current SFR inferred from the 1.4 GHz luminosity vs. the total mass of stars inferred from the R-band luminosity for the objects contained in the radio-selected samples of Benn et al. (1993) and Hopkins et al. (1998). From left to right, the lines indicate the loci of points with characteristic times $\tau = M_{\rm TOT}/{\rm SFR}_{1.4} = 10^8, 10^9$, and 10^{10} yr, respectively.

to-galaxy variation of SFRs, can be seen also in Figure 1 of Devereaux & Young (1990) and Figure 8 of Young et al. (1996), although these authors did not emphasize the discrepancy. On the other hand, investigations spanning a smaller range of luminosities (e.g., Kennicutt 1983b; Lonsdale et al. 1987) have sometimes inferred that the relationship is close to strict proportionality. Devereaux & Young (1990) argue that the general correlation between Hα and FIR results constitutes "strong evidence" for the view that the Hα and the FIR luminosity are produced mainly by massive stars in galaxies with high-FIR luminosity. Lonsdale et al. (1987) argue, on the other hand, that a parallel correlation between the FIR and B-band luminosity implies that the FIR emission in most spiral galaxies is "dominated" by emission due to cool dust that is heated in part by low-mass stars. Even in this case, however, we would expect the FIR luminosity to be increasingly dominated by ionizing radiation in the presence of vigorous star formation.

The systematic overestimate of the SFR derived from Hα relative to the 1.4 GHz estimates at *low* values of SFR is related in part to the difficulty of determining the zero-point level for Hα emission from H II regions in the presence of stellar Hα emission or absorption. Furthermore, since the radio/FIR correlation can be "linearized" by allowing for the escape of cosmic rays from galaxies with weak star formation (Condon et al. 1991a), we must also entertain the possibility that the SFR estimate based on $L_{1.4}$ is actually too low in these objects.

The deviation at high-radio luminosities, as well as the increasing scatter in the correlation, could result from a relatively large amount of extinction in those objects undergoing the most vigorous star formation, from the absorption of Lyman photons by dust, or from an IMF that weights differently the high-mass stars mainly responsible for Hα and the lower mass stars that dominate the supernova numbers (or to a combination of these factors). The fact that the estimates based on the edge-on sample of Lehnert & Heckmann (1996; Fig. 1, *open triangles*) fall systematically low supports the view that extinction plays a particularly significant role. It is notable that the value of SFR derived from Hα tends to be bounded above by a rate of $\approx 25\ M_\odot$ yr^{-1}, corresponding to a luminosity of about 3×10^{35} W Hz^{-1}.

Estimates of the SFR based on U-band observations exhibit considerable scatter with respect to the radio estimates. Like the estimates based on Hα, they tend to be higher at low SFR and lower at high SFR. As noted above, even old stellar populations emit U-band light (e.g., Bruzual & Charlot 1993, their Fig. 1), providing a possible explanation of the trend observed at low values of SFR. The trend for relatively low-SFR values toward the right of the figure could reflect enhanced extinction in vigorous starbursts. As with Hα, there appears to be an upper limit to the SFR derived from U-band measurements. The discrepancies highlighted here need to be further investigated, especially given the increasing use of broad-band, far-UV luminosities to infer SFRs in galaxies with very high redshifts ($z \gtrsim 1$; e.g., Cowie et al. 1997).

The points shown in Figure 2 correspond to galaxies selected by very deep surveys in the radio continuum. Of the star formation indicators discussed above, only radio and Hα luminosities are available at present for these samples. Moreover, the Hα values have been derived from noisy spectra that were obtained to determine redshifts rather than line fluxes, and hence they are expected to show significant scatter. The expedient of rejecting radio-selected objects that are red and/or show absorption line spectra has led to a sample that follows a trend essentially indistinguishable from the "local" sample. It is thus reasonable to conclude the following: (1) the "shortfall" in the Hα estimates of the SFR for the distant sample is similar to that in the local population and is likely to arise for the same reasons, and (2) the radio luminosities of these types of galaxies provide estimates of their current SFRs according to equation (1). A corollary of this is that several faint radio-selected galaxies have SFRs comparable with those of the intrinsically luminous *IRAS* galaxies. There is therefore considerable promise that deep radio surveys will reveal significant numbers of objects similar to the luminous *IRAS* galaxies but lying at higher redshifts.

While the SFR of a galaxy is of interest in its own right, the ratio of the current SFR to the total number of stars that have been formed in a galaxy offers additional insight into the potency of the current rate of star formation. We can estimate the total mass of stars formed in the faint radio galaxies, $M_{\rm TOT}$, by using their R-band luminosities in the relation

$$M_{\rm TOT} = \frac{L_R}{3.4 \times 10^{11}\ {\rm W\ Hz^{-1}}}\, M_\odot\ . \quad (5)$$

Here, we have used the approximation (deduced from Bruzual & Charlot 1993) that steady star formation, with a standard IMF and occurring over a period of more than 1 Gyr, will produce an R-band mass-to-light ratio of $R \approx 5$ mag $M_\odot^{-1}$. Since this approach fails to account for the contribution of any *current* starburst to the R-band luminosity, it will underestimate the fractional amplitude of very strong bursts.

Figure 3 exhibits, for the sample shown in Figure 2, the relationship between the SFR (of massive stars) deduced from the radio luminosity and the total mass of stars deduced from equation (5). Lines are drawn to illustrate the loci of points for which the characteristic time $\tau = M_{\rm TOT}/{\rm SFR}_{1.4}$ is constant. There is a tendency for galaxies that have already formed many stars to support a higher rate of current star formation. There is also a wide scatter in the ratio of SFR to total mass at any chosen size, not all of which is due to errors of observation. There are about a dozen galaxies with a stellar mass $M \approx 10^{10}\ M_\odot$ and a SFR ${\rm SFR}(M > 5\ M_\odot) \geq 10\ M_\odot\ {\rm yr}^{-1}$. For such galaxies, the current burst of star formation is likely to increase the stellar mass by more than 10% if sustained for a time exceeding 10^7 yr, implying an event of considerable significance in the development of the system. These objects are reminiscent of the *IRAS* galaxies that have high values of $L_{\rm FIR}/L_B$ (e.g., Sanders & Mirabel 1996, their § 2.2).

4. PROSPECTS

The utility of decimetric radio luminosity as a measure of the SFR in a galaxy relies on the hypothesis that the radio luminosity is directly proportional to the supernova rate. The radio-FIR correlation can be cited as support for this hypothesis, although the "shortfall" of Hα and U-band predictions (Fig. 1) at high-radio luminosities might be seen as evidence against it. Given the potential rewards of applications of the relation, the astrophysical interpretation of the phenomena controlling the form of Figure 1 must be explored further. There appears to be particular concern regarding the interpretation of values of SFR inferred from UV luminosities. It is evident that an exploration of correlations between *deviations* from the trend lines shown in Figure 1, combined with additional two-color optical and FIR data, could help to elucidate these phenomena.

Armed with the capacity to determine SFRs from radio luminosities, we are in a position to probe the current SFRs of galaxies to redshifts well beyond $z = 0.1$, provided that we can obtain optical identifications and thence redshifts. Optical photometric and spectroscopic observations also help to confirm that the galaxy is not host to a "monster" and to eliminate the possibility this it is radio-loud. *Radio selection* of the candidates will preferentially reveal objects with high rates of current star formation.

We are presently extending the radio frequency sensitivity of the Phoenix survey (Hopkins et al. 1998) using the Australia Telescope and seeking to obtain a large number of redshifts (approaching 500) for the identified radio sources using the 2dF fiber spectrograph on the Anglo-Australian Telescope. These data will significantly enhance our understanding of star formation in the region $0.1 \lesssim z \lesssim 1$.

This research has used the NED, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The research has also used the NVSS database. The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc. The research has been supported by the Australian Research Council and the Science Foundation for Physics within the University of Sydney.

REFERENCES

Allen, D. A., Norris, R. P., Meadows, V. S., & Roche, P. F. 1991, MNRAS, 248, 528
Alonso-Herrero, A., Aragón-Salamanca, A., Zamorano, J., & Rego, M. 1996, MNRAS, 278, 417
Baum, S. A., & Heckman, T. 1989, ApJ, 336, 702
Benn, C. R., Rowan-Robinson, M., McMahon, R. G., Broadhurst, T. J., & Lawrence, A. 1993, MNRAS, 263, 98
Biermann, P. 1976, A&A, 53, 295
Bothun, G. D., Lonsdale, C. J., & Rice, W. 1989, ApJ, 341, 129
Bruzual, A. G., & Charlot, S. 1993, ApJ, 405, 538
Caldwell, N., Kennicutt, R., Phillips, A. C., & Schommer, R. A. 1991, ApJ, 370, 526
Condon, J. J. 1989, ApJ, 338, 13
———. 1992, AR&A, 30, 575
Condon, J. J., Anderson, M. L., & Helou, G. 1991a, ApJ, 376, 95
Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693
Condon J. J., Huang, Z.-P., Yin, Q. F., & Thuan, T. X. 1991b, ApJ, 378, 65
Condon, J. J., & Yin, Q. F. 1990, ApJ, 357, 97
Cowie, L. L., Hu, E. M., Songaila, A., & Egami, E. 1997, ApJ, 481, L9
Devereaux, N. A., & Young, J. S. 1990, ApJ, 350, L25
Eales, S. A., Wynn-Williams, C. G., & Beichman, C. A. 1988, ApJ, 328, 530
Ferrini, F. 1997, in ASP Conf. Ser. 126, From Quantum Fluctuations to Cosmological Structure, ed. D. Vlls-Gabaud, M. Hendry, P. Molaro & K. Chamcham (San Francisco: ASP), 529
Fioc, M., & Rocca-Volmerange, B. 1997, A&A, 326, 950
Gallagher, J. S., & Hunter, D. A. 1987, in Star Formation in Galaxies, ed C. J. Lonsdale Persson (NASA CP:2466), 167
Gallagher, J. S., Hunter, D. A., & Tutukov, A. V. 1984, ApJ, 284, 544
Gehrz, R. D., Sramek, R. A., & Weedman, D. W. 1983, ApJ, 267, 551
Hine, R. G., & Longair, M. S. 1979, MNRAS, 188, 111
Hopkins, A. 1998, PhD thesis, Univ. Sydney
Hopkins, A., Mobasher, B., Cram, L., & Rowan-Robinson, M. 1998, MNRAS, 296, 839
Kennicutt, R. C. 1983a, ApJ, 272, 54
———. 1983b, A&A, 120, 219
———. 1992, ApJ, 388, 310
Kennicutt, R. C., Keel, W. C., van der Hulst, J. M., Hummel, E., & Roettiger, K. A. 1987, AJ, 93, 1011
Kennicutt, R. C., & Kent, S. M. 1983, AJ, 88, 1094
Kennicutt, R. C., Tamblyn, P., & Congdon, C. W. 1994, ApJ, 435, 22
Kirk, J. G. 1994, in Plasma Astrophysics, ed. J. G. Kirk, D. B. Melrose, & E. R. Priest (Berlin: Springer), 225
Kron, R. G., Koo, D. C., & Windhorst, R. A. 1985, A&A, 146, 38
Leech, K. J., Lawrence, A., Rowan-Robinson, M., Walker, D., & Penston, M. V. 1988, MNRAS, 231, 977
Lehnert, M. D., & Heckman, T. M. 1996, ApJ, 472, 546
Lonsdale Persson, C. J., & Helou, G. 1987, ApJ, 314, 513
Pérez-Olea, D. E., & Colina, L. 1995, MNRAS, 277, 857
Romanishin, W. 1990, AJ, 100, 373
Sanders, D. B., & Mirabel, I. F. 1996, AR&A, 34, 749
Sopp, H. M., & Alexander, P. 1991, MNRAS, 251, 14P
Thronson, H. A., & Telesco, C. M. 1986, ApJ, 311, 98
Wall, J. V., & Jackson, C. A. 1997, MNRAS, 290, L17
Young, J. S., Allen, L., Kenney, J., Lesser, A., & Rownd, B. 1996, AJ, 112, 1903
Xu, C. 1990, ApJ, 365, L47