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THE MAGELLANIC IRREGULAR GALAXY NGC 4214: STAR FORMATION AND THE INTERSTELLAR MEDIUM

HARLEY A. THRONSON, JR.,[1] DEIDRE A. HUNTER,[2] C. M. TELESCO,[3]
MATTHEW GREENHOUSE,[1] AND D. A. HARPER[4]
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ABSTRACT

Near- and far-infrared continuum and $J = 1 \rightarrow 0$ CO emission-line observations of the Magellanic irregular galaxy NGC 4214 are presented and discussed. We find that the 160 μm emission is concentrated toward the visually brighter central parts of the galaxy, although there appears to be some low-level emission that extends outward from this core. We observed the $J = 1 \rightarrow 0$ CO line emission in order to estimate the mass of star-forming molecular material in the object. Only if we use a "nonstandard" conversion between CO line strength and H_2 mass does the derived molecular mass agree with that estimated from the cool dust emission. In agreement with earlier results, we believe that the CO line emission underestimates the H_2 mass as a result of lower metallicity in the galaxy. The total current star-formation rate is typical for this type of galaxy, 0.5–1 $M_{\odot}$ yr^{-1}. Based upon analysis of the blue flux, this rate has been maintained to within about a factor of 4 for about a billion years. We do not believe that we are able to estimate the constancy of star formation to better than this factor. The star-formation rate in the center of the galaxy, averaged over a Hubble time, is apparently much lower than the current rate. We calculate that the average efficiency of star formation is about 1.5%, comparable to values found for other star-forming galaxies such as late-type spirals and the Milky Way.

Subject headings: galaxies: individual (NGC 4214) — galaxies: interstellar matter — galaxies: photometry — stars: formation

I. INTRODUCTION

Irregular galaxies are the most abundant members of the class of active star-forming galaxies, many are nearby and can be studied in great detail, and they are moderately bright at visual wavelengths by the standard of modern instrumentation (e.g., Gallagher and Hunter 1984, 1986; Hunter *et al.* 1986; Thuan 1983; Fanelli, O'Connell, and Thuan 1988). Nevertheless, they remain relatively unstudied in detail at wavelengths other than visual, apparently because of the disposition of infrared and radio astronomers toward objects of very high luminosity. Yet, based upon the large number of objects studied using *IRAS* data, some of the most efficient galaxies at forming stars are irregulars (Gallagher, Hunter, and Tutukov 1984; Hunter *et al.* 1986; Thronson and Telesco 1986). Even if irregulars and dwarfs are no more efficient at forming stars than the giant spirals, because they are so abundant, a significant fraction of new stars in the universe are being created in small galaxies.

We are continuing our detailed study of the infrared and radio molecular emission from Magellanic irregular galaxies with NGC 4214 (classified SBmIII). We have recently reported on one of its siblings, NGC 4449 (Thronson *et al.* 1987). In this series of studies, we are using the Kuiper Airborne Observatory to produce far-infrared maps of modest angular resolution to identify the regions of most active star formation. Furthermore, cool emission from dust might be used to reliably estimate the mass of molecular gas. We also obtained $J = 1 \rightarrow 0$ CO spectra of NGC 4214 at about the same angular resolution as the KAO observations for an alternative estimate of the molecular gas mass. We also attempted a small near-infrared map to derive the total stellar mass. Our primary goals are to determine the history of large-scale star formation, efficiency of stellar creation, and the mass of the interstellar medium in small galaxies.

Several authors have investigated star formation and the stellar populations in NGC 4214. Hunter (1982) studied the characteristics of the Hα and visual continuum emission from a number of irregular galaxies, including NGC 4214. Huchra *et al.* (1983) used ultraviolet, visual, and near-infrared data to argue that the galaxy underwent a period of enhanced star formation (a "burst") several times 10^7 years ago that produced $\sim 5\%$ of the stellar mass of the galaxy. An intriguing model has been recently suggested by Hartmann, Geller, and Huchra (1986) in which a recent merger or collision between NGC 4214 and a neighboring galaxy resulted in an infusion of gas and resultant increased rate of star formation. This idea was based upon the complicated velocity field of the gas in the galaxy, a velocity field that is apparently very difficult to sustain for more than a few times 10^8 years. Lovely color images of the galaxy have been presented by Schild (1984, 1988), along with a discussion of the general visual appearance of the galaxy, in which he notes that it is one of the bluest known ($B - V \approx 0.5$), which suggests that star formation has recently been relatively active. A variety of observed and derived parameters for the galaxy are presented in Table 1.

II. OBSERVATIONS

a) The Far-Infrared Observations

NGC 4214 was mapped at 160 μm in 1986 January using the 0.9 m telescope aboard NASA's Kuiper Airborne Observatory. The detector system was a 32-element array of Ge(Ga) bolometer detectors, each mounted behind a light-collecting cone

[1] Wyoming Infrared Observatory, University of Wyoming.
[2] Lowell Observatory.
[3] Space Science Laboratory, NASA/Marshall Space Flight Center.
[4] Yerkes Observatory, University of Chicago.

TABLE 1

NGC 4214 Galaxy Parameters

Parameter	Value
R.A. (1950)[a]	$12^h13^m8^s.2 \pm 0^s.4$
Decl. (1950)[a]	$36°36'30'' \pm 4''$
Classification[b]	SBmIII
Distance	5.4 Mpc
Infrared luminosity[c]	$1.1 \times 10^9\ L_\odot$
Blue luminosity[c]	$5.0 \times 10^8\ L_\odot$
Atomic gas mass[d]	$1.4 \times 10^9\ M_\odot$
Molecular gas mass[e]	$1 \times 10^8\ M_\odot$
Dust mass[f]	$1.8 \times 10^5\ M_\odot$
Total stellar mass[g]	$4 \times 10^9\ M_\odot$
Star-formation rate[h]	$0.7\ M_\odot\ \mathrm{yr}^{-1}$
τ_R[i]	$\geq 2 \times 10^9$ yr

[a] Near-infrared peak, here defined as the nucleus of the galaxy.
[b] *Revised Shapley Ames Catalog* (Sandage and Tammann 1981).
[c] § II*a*, $1\ L_\odot \equiv 3.9 \times 10^{33}$ ergs s^{-1} at all wavelengths, $M_{B,\odot} = 5.48$.
[d] Allsop 1979; Gallagher and Hunter 1985.
[e] Molecular mass for the central core of the galaxy estimated from our $J = 1 \rightarrow 0$ CO data, § III*b*.
[f] Dust mass estimated from our 160 μm data § II*a*.
[g] Total stellar mass, § III*c*.
[h] Star-formation rate, § III*a*.
[i] Roberts time: length of time to deplete all the gas, § III*b*.

TABLE 2

NGC 4214 Far-Infrared Parameters

Parameter	Value
Integrated (Jy):	
12 μm (*IRAS*)	0.39
25 μm (*IRAS*)	1.76
60 μm (*IRAS*)	14.2
100 μm (*IRAS*)	24.8
160 μm (KAO)	19.2 ± 1.7
Peak (45″ beam)	6.8 ± 0.6 Jy
L_{IR} (12–160 μm)	$1.1 \times 10^9\ L_\odot$
T_d[a]	28 K
M_d	$1.8 \times 10^5\ M_\odot$

[a] Assuming emission of the form $\nu^2 B_\nu(T_d)$ fits the 100 and 160 μm integrated flux densities; probably uncertain by $\pm 25\%$.

(Harper *et al.* 1976). At the Nasmyth focus of the telescope, the angular diameter (FWHM) of each circular pixel was $45'' \pm 5''$ and the center-to-center separation was 50″ (45″ corresponds to 1.2 kpc at the adopted distance to the galaxy of 5.4 Mpc). The detector used a broad-band filter with half-power points at $\lambda = 130\ \mu$m and $\lambda = 270\ \mu$m. For a wide range of far-infrared spectra, the effective wavelength was within $\pm 10\ \mu$m of $\lambda = 160\ \mu$m. During the course of the observations, the reference beam spacing was 4′.5, oriented with an average position angle of 135°. This chopper throw is smaller than the 10′.6 Holmberg diameter of the galaxy. However, as discussed below, the far-infrared flux is concentrated to the inner few arcminutes of the galaxy, and we expect little contamination in our reference position from outlying emission. Flux-density calibration was accomplished by observing the far-infrared peak of Ori Molecular Cloud 1 (Thronson *et al.* 1986). We estimate a $\pm 20\%$ (1 σ rms) systematic uncertainty in this calibration.

Serious aircraft turbulence made our observations of NGC 4214 among the most difficult that we have experienced. The object was mapped by using a dim offset star about 5′ away in the focal plane of the telescope, which also added to the large absolute positional uncertainty of our far-infrared observations. For these reasons, our estimate of the absolute accuracy of the position of our far-infrared map of the galaxy, $\sim \pm 25''$, is greater than that quoted in the *IRAS* catalog of galaxies (Lonsdale *et al.* 1985) for the same object. We therefore use the *IRAS* position for the far-infrared maximum, which is at the location of the visual center of NGC 4214, within the uncertainties.

Our 160 μm map of NGC 4214 is superposed upon an Hα image of the galaxy in Figure 1 (Plate 3). A blue-band image of the galaxy on the same scale is shown in Figure 2 (Plate 4). The maximum observed flux density is 6.8 Jy within one beam and the total integrated 160 μm flux density is 19 Jy. Due primarily to systematic calibration uncertainties, we believe that these values are uncertain to about $\pm 20\%$. The contour levels are noted in the caption. In Figure 1, the outermost contour is equivalent to 0.2 of the peak and corresponds to a signal-to-noise ratio of about 2 per beam. The circular, dashed contour is equivalent to about 0.3 of the peak and represents a position at which some channels in our array detector system registered a positive detection, but a repeated observation failed to detect anything. We know of no galaxian feature at this position, which was included by the array when centered on the peak far-infrared position. A summary of the far-infrared data is presented in Table 2.

The infrared spectral energy distribution for the entire galaxy within the outer contour in Figure 1 is shown in Figure 3. *IRAS* data were used for the wavelengths from 12 to 100 μm. We have fitted the longest wavelength points by a function of the form $F_\nu \propto \nu^2 B_\nu(T_d)$, which is appropriate to the far-infrared emission from galaxies (e.g., Telesco and Harper 1980; Rickard and Harvey 1984) and from which we estimate a dust temperature of $T_d = 28$ K. Excess emission above this function, shortward of about 60 μm, shows that a range of warmer dust temperatures is present in the galaxy. Hence, emitting regions with a broad range of physical conditions must be contributing to the observed energy distribution, as expected for a source as complicated as a galaxy (e.g., Cox, Krügel, and Mezger 1986). To find the total infrared luminosity, we integrated under the observed points, from 10 to 160 μm, and extrapolate to longer wavelengths using the curve in the figure. We find $L_{IR} = 1.1 \times 10^9\ L_\odot$ for our adopted distance of 5.4 Mpc.[5] Data from other workers have been corrected, where necessary, to this distance.

For a given dust temperature T_d, the mass of dust in emission at 160 μm is $M_d(M_\odot) \approx 11 D^2(\mathrm{Mpc}) F_\nu[\exp(96/T_d) - 1]$, using parameters and formulation suggested by Hildebrand (1983). In this expression, F_ν is the 160 μm flux density in Jy. For NGC 4214 and $T_d = 28$ K, we calculate $M_d \approx 1.8 \times 10^5\ M_\odot$. Young *et al.* (1986) and Thronson and Mozurkewich (1988) suggest that the molecular gas mass in active star-forming galaxies is about 500 times greater than the mass of dust calculated to be emitting at about 100 μm. In NGC 4214, our far-infrared data indicate, then, $M(H_2) \approx 1 \times 10^8\ M_\odot$ or about an order of magnitude less than the *total* observed H I mass (Table 1). We believe that this difference is larger than the uncertainty in estimating the gas mass from the dust emission. However, the region of 21 cm H I emission is larger in diameter by a factor of 5–10 than the region over which we have

[5] Throughout this work, $1\ L_\odot \equiv 3.9 \times 10^{33}$ ergs s^{-1}, regardless of wavelength, which is not a universal convention.

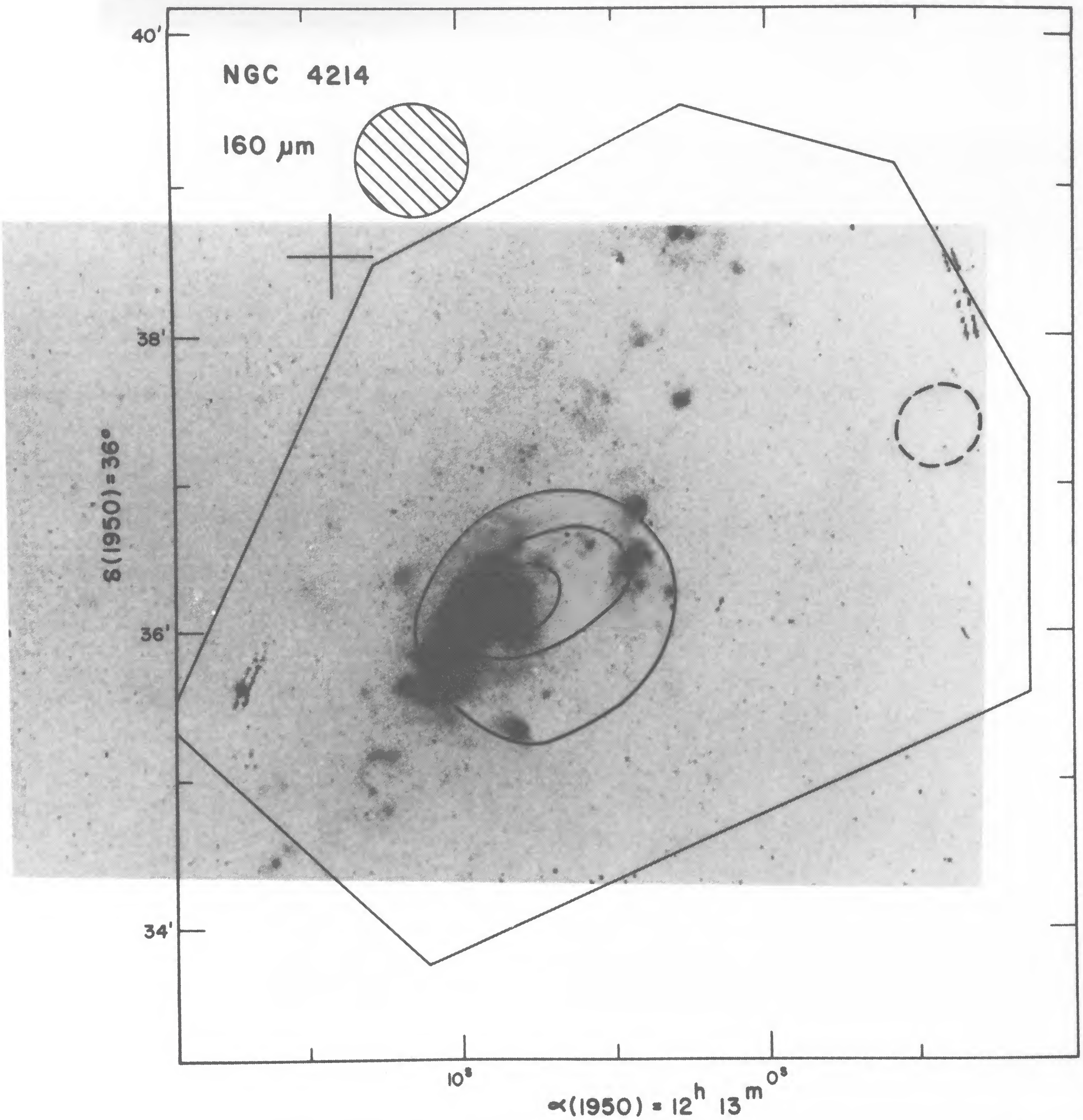

FIG. 1.—Distribution of 160 μm emission from NGC 4214 superposed upon an Hα CCD image of NGC 4214, obtained with the No. 1 0.9 m telescope on Kitt Peak. The far-infrared contour levels are 0.2, 0.4, 0.6, and 0.8 of the peak, where 1.0 = 6.8 Jy in a 45" beam. The dashed contour is the position where emission equal to 0.3 of the peak was detected by some channels of our far-infrared array, but not confirmed in later observations. Our 1 σ noise level is about 0.1 of the peak. The polygon outlines the region included in our far-infrared mapping. We estimated an absolute positional accuracy that is shown by the cross in the upper left of the figure, with each arm 20" long, equal to the 1 σ uncertainty. The far-infrared beam diameter is the hatched circle.

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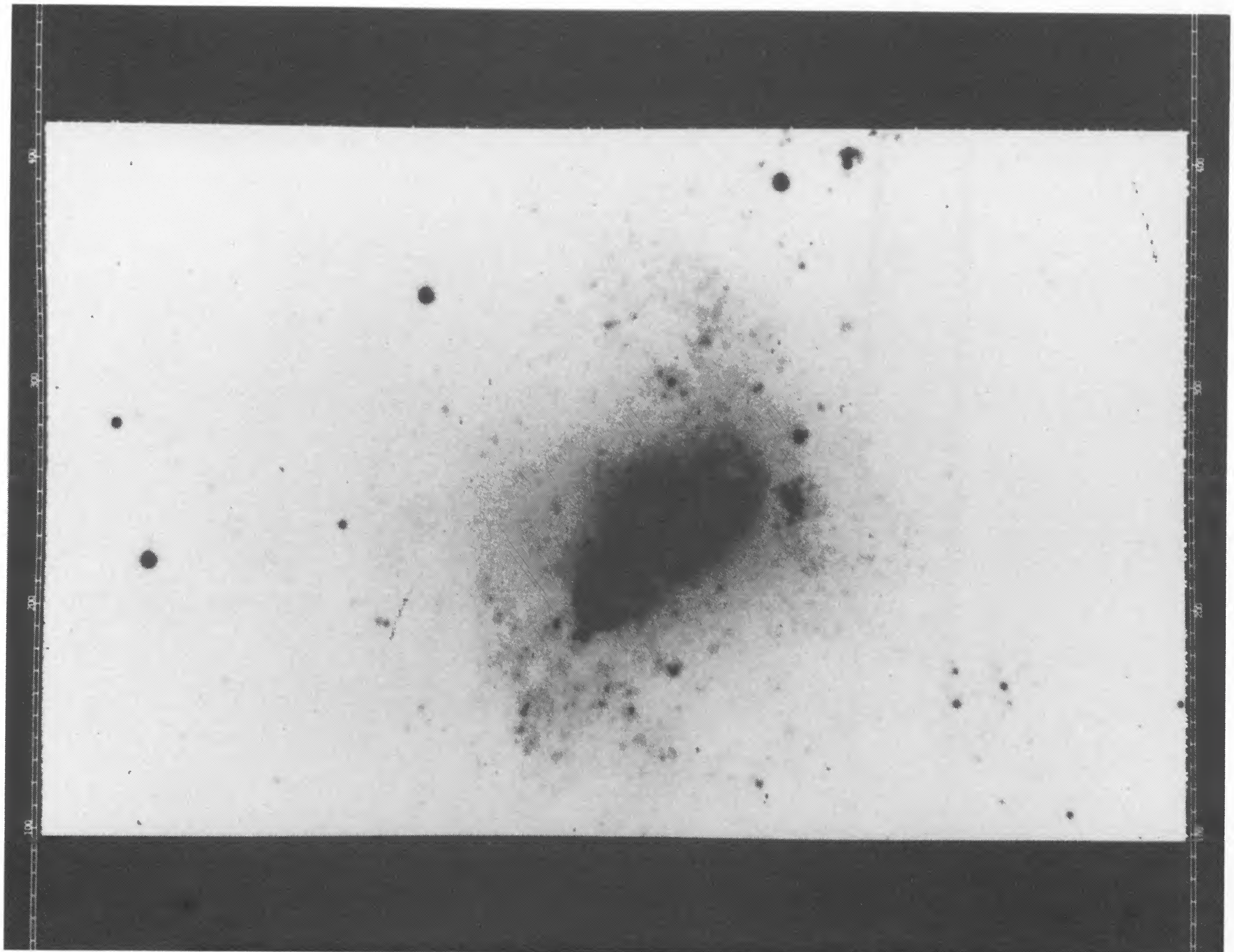

FIG. 2.—A Strömgren *b* CCD image of NGC 4214, obtained with the No. 1 0.9 m telescope on Kitt Peak, reproduced on the same scale as Fig. 1.

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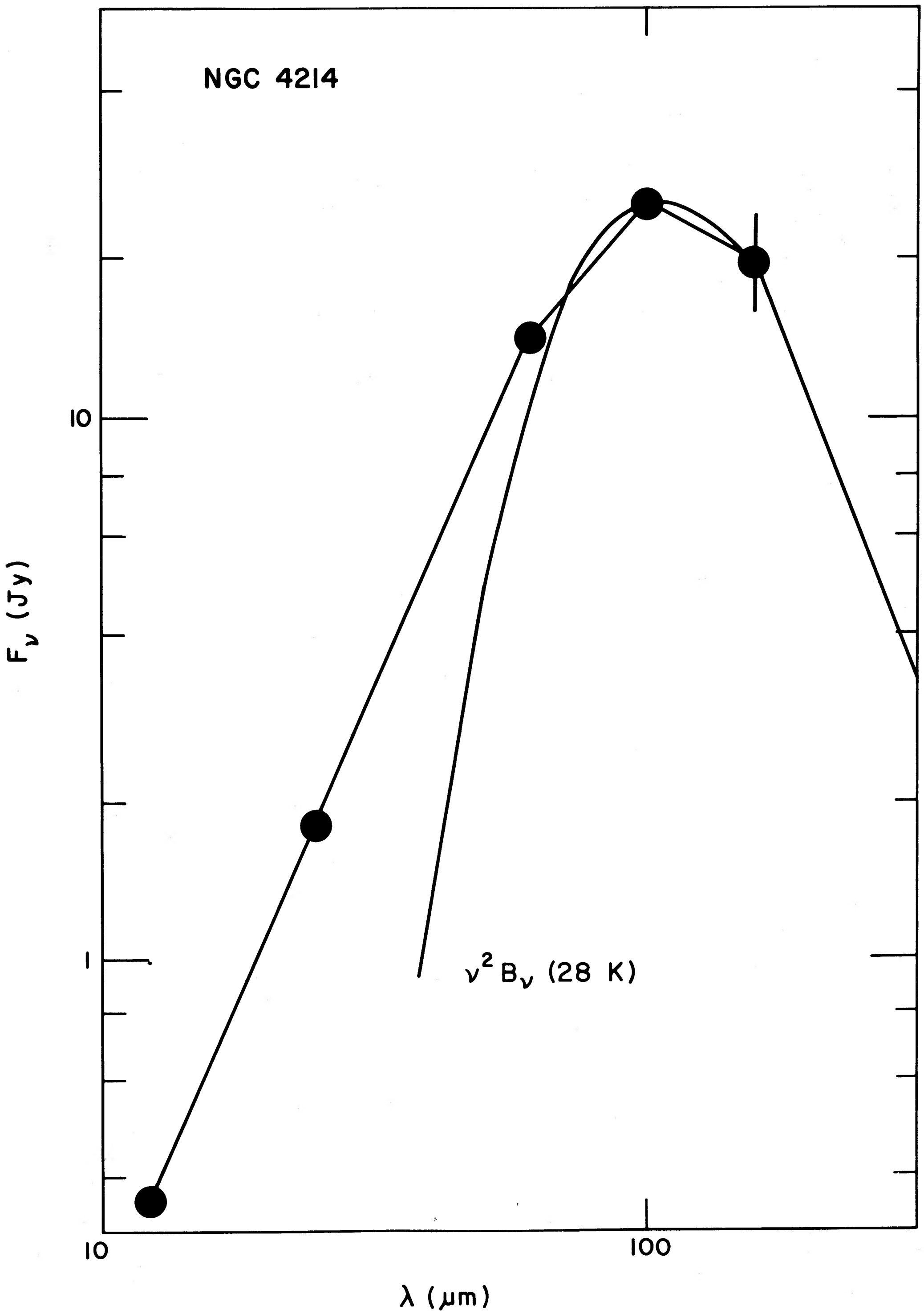

FIG. 3.—The total infrared energy distribution for NGC 4214. Data from the *IRAS* Point Source Catalog were used for the four shorter wavelength points and our KAO observation is the 160 μm point. A function of the form $F_\nu \propto \nu^2 B_\nu(T_d = 28)$ has been fitted to the two long-wavelength points.

detected far-infrared flux (Allsop 1979). We return to the question of the mass of the interstellar medium in § III*b*, where we tentatively conclude that $M(H_2) \approx M(\text{H I})$ over the region where both have been mapped.

b) The Near-Infrared Observations

We mapped a 120″ × 64″ (north-south × east-west) region centered upon the visual nucleus of NGC 4214 in *K* (2.2 μm) using the 2.3 m telescope of the Wyoming Infrared Observatory (WIRO) during 1986 May. Our detector system was a single-channel InSb detector with the standard near-infrared passband filters and a circular beam of FWHM diameter 6″. The detector system used a DC-coupled integrating preamplifier, thus requiring no reference position on the sky. Background flux was removed by identifying regions in the resulting map that appeared devoid of emission from the galaxy, but were characteristic of the sky. The photometric standard was HD 105601 for which we adopted $K = 6.68$.

The peak of the near-infrared emission is coincident with that of the visual center (Dressel and Condon 1976), within the uncertainties of the observations. We found 2.2 μm emission extended over most of the region that we mapped, but at a level of only about 2 σ per beam, with the exception of the immediate vicinity of the nucleus. Thus, we do not present our resultant images of the galaxy. However, our data should be sufficient to estimate the *K* brightness in the central region of NGC 4214. Most of our analysis in the following sections will be limited to the 1′ diameter region centered upon the nucleus. From our data, we estimate $m_K \approx 10.3$ for this region, which is likely to be a lower limit to the brightness of this part of the galaxy since there must be significant low-level emission to which our system was not sensitive. Our results are in agreement with those of Huchra *et al.* (1983). If $V-K \approx 2.2$ for the entire galaxy, which seems a reasonable value (Huchra *et al.*), then $m_K \approx 8.1$ for the entire galaxy. Table 4 summarizes our near-infrared data.

c) The Millimeter-Wave Observations

During 1986 October, NGC 4214 was observed using the 12 m NRAO telescope on Kitt Peak in Arizona.[6]

The system was tuned to detect the $J = 1 \rightarrow 0$ transition of $^{12}C^{16}O$ (hereafter, CO) at 115 GHz using the SIS receiver. At this frequency, the beam size of the telescope is 55″ and we used a reference position 10′ away, in an area found to be devoid of CO emission. Relative calibration was accomplished by the standard NRAO chopper-wheel technique and an absolute calibration was produced by regularly observing IRC +10°216 for which we took $T_R^* = 6.5$ K. Peak antenna temperatures for the calibration objects were repeatable to within ±10% and we estimate that the absolute pointing accuracy of the telescope was ±10″ (±1 σ rms).

Three positions in the galaxy were observed and the results are presented in Table 3. These positions almost cover the region observed to emit at 160 μm, allowing direct, but approximate, comparison with parameters derived from the far-infrared emission. Atomic hydrogen gas is found to extend over the entire galaxy, about 10′ in diameter (Allsop 1979), much larger than our millimeter-wave coverage of the region from which we observed cool dust in emission (Fig. 1). However, there appears to be a bright "core" of H I emission that is roughly confined to the inner part of NGC 4214 that we have observed. Within the uncertainties, our CO line strength at the nuclear position agrees with that of Tacconi and Young (1985) who observed this single point. The observed CO linewidths are comparable to those found for the H I gas (Allsop 1976; Gallagher and Hunter 1986).

[6] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 3

NGC 4214 $J = 1 \rightarrow 0$ CO OBSERVATIONS

Position[a]	$\int T_R^* dv$ (Rb)[b]	V_{LSR} (km s^{-1})	Δv[c] (km s^{-1})
(0, 0)	1.0 ± 0.35	290	60
(0.32, −0.12)........	1.5 ± 0.3	280	55
(0.64, −0.25)	1.3 ± 0.25	310	85

[a] Positions are given with respect to the nuclear position (Table 1) in units of arcmin (Δα, Δδ), with minus directions being west and south.

[b] 1 Reber (Rb) ≡ 1 K km s^{-1}.

[c] Δ*v* is the estimated full width of the CO line at zero intensity.

III. ANALYSIS AND DISCUSSION

a) The Far-Infrared Emission

Figure 1 shows that the 160 μm emission region of the galaxy approximately overlaps the brighter Hα emitting core of the galaxy and both are 1′–2′ across. This general agreement is expected for the two tracers of active star formation. However, to put our maps in proper perspective, note that the Holmberg diameter of this galaxy is 10′.6! Therefore, both the bright far-infrared and Hα emission are limited to the central core of the galaxy. In a similar way, we also found the far-infrared emission from the irregular galaxy NGC 4449 to be limited to its central regions (Thronson *et al.* 1987). NGC 4214 does not have a well-defined galactic nucleus, although there is bright visual emission close to the center of brightness of the galaxy. This core is noncircular, amorphous in appearance, but is also the location of the maximum near-infrared emission, within the positional uncertainties. We assume that this stellar "enhancement" is the anemic irregular-galaxy equivalent to the nuclei in spiral galaxies.

Figure 1 suggests that there is some extended far-infrared emission lying outside the bright Hα emitting core, but the data are of insufficient angular resolution to make a more definite statement. In our NGC 4449 paper, we discussed the role of a strong general interstellar radiation field in heating widely distributed dust. It was for this reason, we concluded, that NGC 4449 shows a far-infrared energy distribution that rises steeply at wavelengths longward of 100 μm, consistent with a moderately large amount of cool dust, distributed throughout that galaxy. NGC 4214, on the other hand, shows no strong evidence for such extended emission, either in our 160 μm map or in its far-infrared spectrum (Fig. 3). The luminosity of NGC 4214 is about one-third that of NGC 4449, in which case the former galaxy would be expected to heat a smaller region of extended material. Furthermore, it is possible that star formation in NGC 4214 is more concentrated than in NGC 4449, in the sense that the stellar radiation is more confined to local regions of stellar creation. We suggest in § III*c* that star formation migrates from position to position in this galaxy and, at present, is concentrated close to its center.

Most likely, in our view, is the possibility that the interstellar medium (ISM) is distributed substantially differently in the two galaxies. Although superficially similar, our far-infrared results suggest that the distribution of cool dust in NGC 4449 and NGC 4214 is not the same. However, the only component of the ISM that has been extensively mapped in the two galaxies is H I. Allsop (1979), as already noted, found 21 cm line emission concentrated toward the core of NGC 4214 and extended at a lower level throughout the full visible area of the galaxy. In sharp contrast, much of the atomic gas in NGC 4449 has been found to be concentrated in a great ring centered on, but outside of, the bright core of the galaxy (J. van Gorkom and D. Hunter, private communication). Whatever the dynamical or evolutionary reason for the different H I structures in the two galaxies, there appears to be a large amount of "inert" (atomic) gas and, presumably, dust surrounding the core in NGC 4449 than is the case in NGC 4214. This different structure could lead directly to the different far-infrared spectral energy distribution and 160 μm appearance.

At wavelengths shortward of around 100 μm, both NGC 4214 and NGC 4449 have similar far-infrared spectra. In turn, their spectra are similar to the variety of the infrared spectra in the small star-forming galaxies studied by Thronson and Telesco (1986). In general, these objects have relatively "hot" dust in emission (i.e., a high ratio of 60 μm flux density to 100 μm flux density), which is usually interpreted as a signature of the emission from active star formation dominating that from inert infrared "cirrus" emission, as expected (see also Hunter *et al.* 1986).

We may use the far-infrared luminosity to estimate the present rate of star formation in the galaxy. Recently, Thronson and Telesco (1986) calculated that the present-day star formation rate may be found via

$$\dot{M}_{\rm IR}(M_\odot\ {\rm yr}^{-1}) = 0.65 \times 10^{-9} L_{\rm IR}(L_\odot) \quad (1)$$

for the Salpeter initial mass function (IMF) from 0.1 to 100 $M_\odot$. For the Miller-Scalo function over the same mass range, the coefficient in equation (1) becomes 2.2×10^{-9}. The difference between these two functions may be thought of as a rough measure of the uncertainties in estimating any quantity from an adopted IMF. In the following discussion, we will adopt results calculated using the Salpeter function.

For the region mapped in the far-infrared, we find a current stellar mass formation rate of 0.7 $M_\odot$ yr^{-1}. If the infrared luminosity is proportional to the 160 μm flux density, then our data (Fig. 1) may be used to estimate the star-formation rate within the 45″ (1.2 kpc) diameter KAO beam at the far-infrared maximum: 0.3 $M_\odot$ yr^{-1}. Gallagher, Hunter, and Tutukov (1984) also calculated the mass-formation rate using the Salpeter function, but used visual data for the entire galaxy. They found $\dot{M} \approx 0.4\ M_\odot$ yr^{-1}, somewhat lower than the value that we derive here. It is possible that star formation is presently limited to the central few arcminutes of the galaxy, from which we find stronger far-infrared emission. If this is the case, the agreement between ourselves and Gallagher, Hunter, and Tutukov is satisfactory.

A major uncertainty in the estimation of star-formation rates from far-infrared data is identifying the source of heating for the grains that we observe in emission. We have assumed here that all the infrared flux arises from dust heated by newly formed stars. For a number of years, some authors have warned that older stars can contribute significantly to the heating of dust that is widely distributed throughout a galaxy. Some of the most complete discussions of this problem have recently been given by Mezger, Mathis, and Panagia (1982) and Persson and Helou (1987). In very active star-forming galaxies, such as the Magellanic irregulars, it is likely that the heating of the dust is dominated by the youngest stars. For example, Thronson and Telesco (1986) found a good correlation between far-infrared and Hα flux for these objects. Furthermore, they found that both tracers of star formation gave similar values for calculated star-formation rates. We are, therefore, confident of our assumption that the infrared luminosity is directly related to the current star-formation rate in the particular case of NGC 4214.

A second major uncertainty in estimating star-formation rates is the IMF that must be adopted. Some recent work has indicated that rather than a single function, a variety of IMFs, along with variable upper and lower mass limits should be seriously considered. Scalo (1988) has summarized and critically examined these important ideas and concluded that there is very little observational evidence at present for bimodal IMFs, and their limits, that have been proposed. We agree with Scalo's conclusion, in a large part because any alternative would lead both to ambiguous results in our analysis and, perhaps, needlessly complicated calculations. We emphasize, however, that the debate over extragalactic IMFs is *very* active at present.

b) The Molecular Gas Emission and the Efficiency of Star Formation in NGC 4214

Detection of the $J = 1 \rightarrow 0$ emission from CO should allow us to estimate the mass of molecular material in the galaxy and, thus, the efficiency of star formation. The key assumption in an analysis of this type is that the CO line strength is an accurate quantitative tracer of the total molecular gas mass. This assumption has been argued most effectively for spiral galaxies by J. Young, N. Scoville, and coworkers (e.g., Young and Scoville 1982; Young *et al.* 1986; see also Polk *et al.* 1987) and supported theoretically by, for example, Dickman, Snell, and Schloerb (1986). However, Maloney (1987) and van Dishoeck and Black (1988) have criticized universal application of a constant conversion of CO line intensity to H_2 mass, particularly in the case of low-metallicity galaxies. Israel *et al.* (1986) proposed a model for CO emission from the Large Magellanic Cloud in which the lower heavy element abundance and stronger ultraviolet radiation field resulted in weak CO line emission despite significant molecular mass. For the similar galaxy NGC 4449, Thronson *et al.* (1987) suggested that the conversion of $I_{\rm CO}$ to $M(H_2)$ appropriate to normal spiral galaxies, underestimates the molecular mass by factors of 3–10, once again due to lower metallicity. Thus, at present, there is substantial evidence that a universal value for converting CO line intensity to molecular gas mass does not exist, due primarily to the effects of variable heavy-element abundances. Based on the work of Israel *et al.*, Maloney (1987), van Dishoeck and Black, and Thronson *et al.*, we adopt for NGC 4214

$$N_{\rm H_2}({\rm cm}^{-2}) \approx 2 \times 10^{21} I_{\rm CO}({\rm Rb})\ , \quad (2)$$

which may be converted to

$$M_{\rm H_2}(M_\odot) \approx 3 \times 10^7 I_{\rm CO}({\rm Rb}) \quad (3)$$

for the beam size of the NRAO telescope at the distance of NGC 4214 (5.4 Mpc). Here 1 Reber (Rb) $\equiv$ 1 K km s^{-1}. At present, a moderately wide range of alternative conversion

TABLE 4

NGC 4214 NEAR-INFRARED OBSERVATIONS

Parameter	Value
Nuclear position	$\alpha(1950) = 12^h13^m8^s.2 \pm 0^s.4$ $\delta(1950) = 36°36'30'' \pm 4''$
Peak brightness and colors[a]	$K = 13.5 \pm 0.1$, $H-K = 0.05 \pm 0.1$, $J-H = 0.7 \pm 0.1$
Total brightness	$K \approx 8.1$

[a] 6".5 beam (full width, zero intensity); 60" north-south chopper throw.

factors have been suggested for low-metallicity galaxies and the conversion factors that we adopt above are about a factor of 5 greater than those originally proposed for spirals (the Young-Scoville relation), although about 10 times greater than the average value recently suggested by Polk *et al.* The heavy-element abundance in this galaxy is about a factor of 2 less than solar (Hunter, Gallagher, and Rautenkranz 1982) and present evidence suggests, very roughly, that the conversion factors should vary with the metallicity as $[X]^{-1.5}$, where [X] is the metallicity of a galaxy relative to that in the Milky Way ISM. Thus, we have adopted an increase in the Young-Scoville relation of a factor of 5 for NGC 4214. If these arguments do not apply to this galaxy, and the Young-Scoville relation is, in fact, more accurate, then the estimate of the H_2 mass that we produce here is an overestimate of the true value by a factor of 5–10.

The values in Table 4 allow an estimate of the mass of molecular material in the bright core of the galaxy. Tacconi and Young (1985) observed the nuclear position using the Five College 14 m radio telescope and our observational results agree with theirs within the uncertainties. Using the conversion relations above, we estimate a molecular mass of $3 \times 10^7\ M_\odot$ for the 55" diameter region centered upon the nucleus and $\sim 1 \times 10^8\ M_\odot$ for the bright core of the galaxy, about 2' across. Normal spiral galaxies generally show $M(H_2) \geq M(\text{H I})$ near their centers, but the H_2 mass that we derive for NGC 4214 is about an order of magnitude less than the total H I mass from 21 cm observations (Table 1). However, over the same core region that we are emphasizing in this study, we estimate $M(\text{H I}) \approx M(H_2)$ and, by the simple measure of $M(H_2)/M(\text{H I})$, this Magellanic irregular, with its very different structure, appears no different from the giant spirals. Furthermore, our calculated H_2 mass is comparable to the gas mass derived from the dust mass in emission at 160 μm (§ II*a*). We emphasize that the agreement between the masses derived from the far-infrared emission and the CO line strength is possible only with our "alternative" CO-to-H_2 conversion factor (eqs. [2] and [3]).[7]

The mass of young stars presently forming may be estimated by adopting the Salpeter IMF from 0.1 to 100 $M_\odot$, for which the mass-to-luminosity ratio is $1.3 \times 10^{-3}\ M_\odot\ L_\odot^{-1}$ (Thronson and Telesco 1986). Using the far-infrared luminosity, the mass of newly formed stars is about $1.5 \times 10^6\ M_\odot$. If these stars are forming out of the molecular material, whose mass we estimated above, they are doing so with an instantaneous efficiency of about 1.5%, defined as the ratio of the mass of young stars relative to the mass of molecular gas from which the stars are assumed to have been born. This value is similar to that estimated for the Milky Way and a handful of other star-forming giant galaxies, assuming that the Salpeter function is applicable (e.g., Young *et al.* 1986; Rengarajan and Verma 1986; Thronson *et al.* 1987).

We note that had we adopted the factor originally suggested by Young and Scoville for converting I_{CO} into molecular mass for giant galaxies, the efficiency of star formation, as we have used the term here, would be extremely high, about 8%, because a lower molecular mass would have been derived. Although very high efficiencies may occur in certain situations, present evidence suggests that star formation in irregular galaxies is not proceeding in any drastically different way from that found for our neighborhood in the Milky Way or in other well-studied galaxies (e.g., Hunter and Gallagher 1986; Scalo 1988). We believe that, except in rare instances, star formation is a local process, governed primarily by processes that are independent of the type of galaxy within which it is taking place. Since the value for the efficiency that we estimate is comparable to that derived for normal spiral galaxies, as discussed above, once again, observations of irregulars demonstrate that large-scale differential rotation and the presence of spiral structure is not necessary to maintain relatively efficient star formation. Furthermore, modest efficiencies also indicate that star formation from *atomic* gas, which has been suggested on a variety of occasions, is not necessary to explain stellar birth in irregulars.

Based upon the preceding discussion, the total H I mass (Table 1) may be a crude measure of the total gas mass in the galaxy, within a factor of 2 or 3. If that is the case, the present rate of star formation for the galaxy, $\sim 1\ M_\odot\ \text{yr}^{-1}$ (previous section), can be maintained for at least 2×10^9 yr. Large amounts of as yet undetected molecular mass, plus return of processed material to the interstellar medium, would extend this lifetime. Alternatively, significant star formation in the outer part of the galaxy, with far-infrared emission at a level below that which we can detect, would shorten our estimated remaining lifetime. However, the Hα image reproduced in Figure 1 shows no evidence for significant star formation outside the central core of the galaxy and Gallagher, Hunter, and Tutukov (1984) found a *total* star-formation rate in fair agreement with that which we derive for the center few arcminutes of the galaxy. As noted in the Introduction, and discussed in the following section, it is possible that the star-formation rate, averaged over a long period of time, is somewhat lower than 1 $M_\odot\ \text{yr}^{-1}$, in which case, the time remaining for star formation to continue (sometimes referred to as the "Roberts time") is likely to significantly exceed the value calculated here.

c) The Near-Infrared Emission, the Stellar Mass, and the History of Star Formation in NGC 4214

The limited near-infrared multicolor photometry that we obtained for the nucleus of NGC 4214 (Table 4) is consistent with the assumption that the emission at these wavelengths arises primarily from an old stellar population, perhaps with some younger stars included (see also Huchra *et al.* 1983), which would give the galaxy its distinct bluish color (Schild 1984, 1988). Frogel *et al.* (1978) and Persson *et al.* (1983) presented the infrared colors of globular clusters, elliptical galaxies, and the nuclei of spirals, all of which have near-infrared colors similar to that which we find for the nucleus of NGC 4214. Thus, a wide variety of galaxies are characterized by

[7] We hesitated to refer to eqs. (2) and (3) as an "alternative" form because the galaxies for which we believe that it approximately applies (star-forming dwarfs and irregulars) outnumber the spirals for which the "standard" Young-Scoville conversion is more accurate.

emission at near-infrared wavelengths from stars born long before the present epoch of active stellar creation. An important use of accurate multiband photometry is to estimate the star-formation rate as a function of time for galaxies. Kennicutt (1983) and Gallagher, Hunter, and Tutukov (1984) first described the method for visual wavelength line and continuum data and we shall apply the same general technique to the infrared data. We find that our data are consistent with a high, relatively constant star-formation rate over the last few billion years, but a present rate that is somewhat higher than that averaged over a Hubble time. However, our analysis is not sensitive to variations in the rate of star formation of a factor of about 4 or less. Our multiwavelength observations are only complete over about the central 1′ (1.6 kpc) of the galaxy and we are, therefore, emphasizing the star-formation history of this region. We shall discuss more superficially the star-forming history of the entire galaxy.

Current rates of star formation for the cental 1′ of the galaxy can be estimated from the far-infrared observations (§ III*a*). In this calculation, we assume that the infrared luminosity scales directly with the 160 μm flux density that we observe. Thus, the luminosity within one 45″ KAO beam at the position of the nucleus about 3×10^8 $L_\odot$. Using the conversion factor suggested by Thronson and Telesco, we estimate a star-formation rate of about 0.3 $M_\odot$ yr^{-1} within the KAO beam, as discussed in § III*a*. Star-formation rates in the recent past may be estimated from the blue luminosity. Gallagher, Hunter, and Tutukov and Thronson and Telesco discuss the source of blue flux from star-forming dwarf galaxies, arguing that stars formed over the range 0.5 to 1×10^9 yr ago dominate the emission at this wavelength. Thus, the blue luminosity is a measure of the star-formation rate averaged over this period of time. Thronson and Telesco estimated the star-formation rate using L_B via

$$\dot{M}_B(M_\odot \text{ yr}^{-1}) = 6.5 \times 10^{-9} L_B(L_\odot) \quad (4)$$

(see the Appendix in Thronson and Greenhouse [1988] for a discussion of the variety of blue luminosities that appear quoted in the literature). The data in Figure 2 were used to estimate that the central 1′ of the galaxy has a blue luminosity of 1.4×10^8 $L_\odot$, indicating a star-formation rate of 0.9 $M_\odot$ yr^{-1}. This is 3 times larger than the *current* rate that we estimated above from the far-infrared observations, which we consider to be fair agreement. Slight beam size differences, along with statistical uncertainties in the observations and systematic uncertainties in the analysis, may account for most of this difference. With relatively large systematic uncertainties in this type of analysis, we must conclude that our data are consistent with star formation proceeding in the core of NGC 4214 at a moderately high rate (for the size region under consideration). Furthermore, this rate has been constant for at least the last billion years and is 0.5–1 $M_\odot$ yr^{-1}, to within a factor of 2 or 3.

A star-formation rate averaged over a Hubble time, 1.5×10^{10} yr, may be estimated from our near-infrared data, assuming that old stars dominate the emission at these wavelengths. Thronson and Greenhouse (1988) describe a method to estimate the total stellar mass in star-forming galaxies using *J*, *H*, or *K* band brightness. Their technique uses the local solar neighborhood as a model for the product of billions of years of normal star formation. They discuss in some detail the applicability of their technique to other types of galaxies. If it applies to NGC 4214, then the mass of stars can be estimated via $M_*(M_\odot) \approx 2.5 \times 10^8 D^2$ (Mpc) F_K (Jy). Applied to the central 1′ region of the galaxy that we mapped at 2.2 μm the stellar mass is 4×10^8 $M_\odot$ for $m_K = 10.3$ (§ II*b*). Over a Hubble time, an average rate of 0.025 $M_\odot$ yr^{-1} could produce this stellar mass. This value is an order of magnitude less than *recent* or *current* rates calculated above from the blue or far-infrared luminosity. We believe that this factor is larger than the uncertainties in our methods and conclude that the galaxy is likely to be undergoing a period of enhanced star formation in its center that has been constant to within a factor of 4 for about the last billion years. We repeat our note from § II*b* that our value for the total *K* brightness from the center of NGC 4214 is almost certainly low. Thus, the average star-formation rate over a Hubble time is probably higher than that which we calculate here. Note also that we have implicitly adopted the current view that irregular galaxies do not have initial periods of star formation that would produce a significant fraction of the total number of stars (Gallagher, Hunter, and Tutukov 1984; Sandage 1986).

The *total* galaxian stellar mass may be found by using the total estimated *K* flux density, $F_K \approx 0.45$ Jy (§ II*b*), and the relation found by Thronson and Greenhouse (above); at 5.4 Mpc, $M_* \approx 3.5 \times 10^9$ $M_\odot$. This value is at the low end of the range of masses summarized by Allsop (1979), but agrees with a number of previous determinations. Over a Hubble time, a star-formation rate of about 0.2 $M_\odot$ yr^{-1} would be sufficient to create the estimated stellar mass of the entire galaxy. This rate is close to that estimated from our far-infrared observations, although because of the large systematic uncertainties, good agreement must be largely fortuitous. Keeping the uncertainties in mind, the straightforward interpretation is that the star-formation rate for the entire galaxy has been roughly constant since NGC 4214 formed, to within a factor of 4. However, different parts of the galaxy, such as the center, have experienced periods of enhanced and, presumably, depressed stellar creation.

In addition to tabulating total stellar masses, Allsop also listed H I masses derived over the years. Typically, previous estimates of the total gas-to-stars mass ratio are close to that which we derive from the data in Table 1: about 25%. This value emphasizes one of the long-standing reasons for the scientific interest in galaxies such as NGC 4214. Not long in the past, based upon the estimated average star-formation rate, the object was almost entirely gas. For a minimum total rate of star formation estimated for the entire galaxy, $\dot{M} = 0.5$ $M_\odot$ yr^{-1}, NGC 4214 was about one-half gas only 3×10^9 yr ago and approaching 75% gas at only about half a Hubble time in the past. Presumably it is the large gas fraction in the irregulars that allow long periods of enhanced star formation.

In the "burst" model of Huchra *et al.* (1983), about 5% of the stellar mass in the galaxy has been created within the last 2–10 $\times 10^7$ yr. Similar conclusions were reached by Thuan (1985). For a total galaxian mass of 4×10^9 $M_\odot$, their model would require an average star-formation rate of 2–10 $M_\odot$ yr^{-1}, which is significantly higher than that which we estimated using the far-infrared luminosity for the galaxy. However, once again we emphasize the systematic uncertainties in this type of comparison and the uncertainties in the various observations are large enough to significantly lower the star-formation rate required by the models of Huchra *et al.* and Thuan. Furthermore, our analysis is not sensitive to active stellar creation in the range of times studied by these other authors. We conclude by noting that our results do not support the "burst" model of Huchra *et al.* and we note that

Gallagher, Hunter, and Tutukov (1984), using visual-wavelength line and continuum emission, concluded that star formation has been proceeding at approximately a constant rate in most irregular galaxies, including NGC 4214.

VI. SUMMARY

We have used near- and far-infrared data and millimeter-wave CO observations to study the star-forming properties of the Magellanic irregular galaxy NGC 4214 and its interstellar medium. We summarize our results as follows.

The galaxy is forming stars at present at ~ 0.5–$1\ M_\odot\ \mathrm{yr}^{-1}$ in its central few arcminutes, if the new stars follow the Salpeter initial mass function from 0.1 to 100 $M_\odot$. This has been maintained for around a Hubble time, although we believe it possible that some regions of the galaxy undergo periods of enhanced and depressed star formation. We do not believe that our estimates of the rates of star formation are accurate to better than a factor of 4.

The efficiency of star formation is difficult to estimate, primarily because the H_2 mass, presumably from which the stars are born, cannot be measured directly. Based on the mass of dust in emission at 160 μm, a plausible efficiency is around 1.5%, if the H I gas does not take part in forming stars. Molecular masses derived using the $J = 1 \rightarrow 0$ CO line and a conversion to $M(H_2)$ appropriate to spiral galaxies produces a mass estimate that is too low by a factor of 5–10. This is due primarily to the lower heavy-element abundance in the galaxy. including the atomic gas, there is enough fuel to form stars for at least 4×10^9 yr at the present rate. The mass of atomic gas is roughly equal to the mass of molecular gas over the region that both are observed. The galaxy is at least 25% gas, by mass, and in the not-so-distant past, NGC 4214 would have been almost entirely gas.

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M. A. GREENHOUSE and H. A. THRONSON: Wyoming Infrared Observatory, Box 3905, University of Wyoming, Laramie WY 82071

D. A. HARPER: Yerkes Observatory, Box 258, Williams Bay WI 53191

D. A. HUNTER: Lowell Observatory, 1400 West Mars Hill Road, Flagstaff AZ 86001

C. M. TELESCO: Space Science Laboratory ES-63, NASA/Marshall Space Flight Center, Huntsville AL 35812