THE ASTROPHYSICAL JOURNAL, 327:671–679, 1988 April 15

NEAR-INFRARED MASS-TO-LIGHT RATIOS IN GALAXIES: STELLAR MASS AND STAR FORMATION IN THE HEART OF THE WHIRLPOOL

HARLEY A. THRONSON, JR., AND MATTHEW A. GREENHOUSE
Wyoming Infrared Observatory, University of Wyoming
Received 1987 June 26; accepted 1987 October 13

ABSTRACT

We use the observed stellar population in the solar neighborhood to derive a relationship between the local stellar mass density and the visual and near-infrared brightness, which we then extend to apply to a wide range of galaxies. Use of the solar neighborhood as a model for the infrared light from a variety of galaxies is justified by evidence that the emission at $\lambda \approx 1$–$2.5\ \mu$m is dominated by low- to moderate-mass red giants. For many objects, these stars should be produced in proportion to the number of older main-sequence stars, which will dominate the total stellar mass. We compare our results with dynamical masses determined for a number of galaxies. The agreement is good.

To apply our technique, we present and discuss near-infrared (J, H, and K) images of the central 2.3 kpc (50″) of the Whirlpool Galaxy (M51, NGC 5194). This object has an elliptical brightness distribution at these wavelengths similar to that reported at longer visual wavelengths. Over the region that we map in the near-infrared, we find a total stellar mass of $M_{*,\mathrm{old}} \approx 1.2 \times 10^{10}\ M_\odot$. From far-infrared photometric data, we find that over the same region, stars are presently being born at a rate of $\sim 4\ M_\odot\ \mathrm{yr}^{-1}$, which is about a factor of 5 greater than the rate averaged over a Hubble time. Therefore, the center part of M51 appears to be undergoing a period of enhanced star formation. However, the present efficiency of star formation, defined as the ratio of the mass of new stars to the mass of star-forming gas, is only $\sim 1\%$, quite comparable to the global value for the Milky Way and other galaxies. We estimate that the current high rate of star formation can last no more than another 10^8 yr or so and, if a large fraction of the stars in the nucleus of M51 was created in periods of enhanced formation, the duty cycle for such events is roughly 5%. In the Appendix, we compare the three different definitions of blue luminosity that are widely used at present.

Subject headings: galaxies: individual (M51) — galaxies: nuclei — galaxies: stellar content — photometry — stars: formation.

I. INTRODUCTION

In the extensive literature on near-infrared imaging and photometry, authors almost invariably state that a prime motivation for observations between 0.8 and 2.5 μm is that this emission is dominated by photospheric light from an old and abundant stellar population. Therefore, the "underlying" stellar mass distribution of galaxies can be revealed through mapping at these wavelengths. Revealed, perhaps, but not easily quantified. As with all population synthesis schemes for broad-band data, there is a wide range of stellar types that can duplicate near-infrared colors of composite systems such as galaxies. That is, while the distribution of an old stellar population may be studied by near-infrared mapping, a reliable mass estimate for these stars is difficult to unambiguously produce. In this paper we use the solar neighborhood as a model for regions of long-term star formation in galaxies and derive near-infrared and visual mass-to-light ratios. We compare our results with other estimates, derived primarily from rotation-curve data. We concentrate almost entirely upon near-infrared photometry because, although abundant moderate-mass main-sequence stars contribute significantly to the visual light from galaxies, so do the rare early-type stars. Furthermore, the near-infrared is much less susceptible to the effects of interstellar extinction.

To apply our technique, we mapped the near-infrared emission from the core of the Whirlpool Galaxy [M51, NGC 5194; classified as an Sbc(s)I–II], which is one of the nearest giant spiral galaxies; it is nearly face-on, and is relatively bright over a wide range of wavelengths. It has thus been a centerpiece of study since the late 1950s, when it became widely realized that activity of an unusual nature dominated the emission from the cores of many galaxies. Ambartsumian (1958), in a vigorously eccentric series of conjectures about galaxian activity, and Woltjer (1959) are among the first to identify galactic nuclei as sites of some kind of high-energy activity. Burbidge and Burbidge (1962) produced one of the early, relatively complete models for the strong emission-line spectra that were becoming widely available a quarter century ago. Not much later, Morgan and Osterbrock (1969) summarized the variety of proposed mechanisms that might explain the nature of nuclear sources, presaging much recent work. Peimbert (1968) and Weedman (1969) both concentrated specifically on M51, concluding that the unusual nucleus of this galaxy is only a few arcseconds across and is much less energetic than that found in the cores of what are today usually referred to as "active" galaxies. Because of this work, astronomers have generally interpreted emission from the central regions of the Whirlpool, outside the nucleus, as dominated by more or less mundane processes such as star formation or stellar photospheric emission.

Smith (1982) presented a low-resolution, far-infrared map of the Whirlpool Galaxy, which should trace the sites of active star formation. He showed that, while emission is present throughout the disk of M51, the central arcminute of the galaxy is by far the brightest region and contributes one third of the total galaxian luminosity at wavelengths longward of

$\sim 30\ \mu$m. Scoville and Young (1983) mapped the emission from the $J = 1 \rightarrow 0$ transition of CO at about the same angular resolution as Smith's far-infrared data and found that the molecular emission followed the far-infrared emission quite well. It is presently popular to argue that the CO emission is proportional to the amount of molecular gas in the telescope beam. Thus, if the far-infrared emission is dominated by emission from star-forming regions, the number of young stars per unit mass of molecular material changes only modestly throughout much of the galaxy. More recently, Palumbo *et al.* (1985) imaged the entire galaxy in X-ray light, the intensity of which closely follows the CO, Hα, and radio continuum emission.

Other recent observations have attempted to study small-scale structure in the core of M51. Lo *et al.* (1987) mapped the $J = 1 \rightarrow 0$ CO emission with an angular resolution of 7″ over a $2' \times 1'$ region, clearly delineating molecular spiral arms that can apparently be traced to within $\sim 30''$ of the galaxy's center. However, the total line flux measured by their interferometer is only about one-third of that measured by low–angular-resolution instruments over the same region, which means that two-thirds of the molecular material in the core lies outside the obvious spiral arms and is presumably distributed more uniformly throughout the core region. Telesco, Decher, and Gatley (1986) found extended, low–surface-brightness 10 μm emission throughout the central 1′ of the galaxy, not clearly associated with any particular feature, including the visually bright nucleus. However, a pair of spiral arms can perhaps be identified in their data. Thus, if emission at mid-infrared wavelengths traces the location where stars are being born, Telesco, Decher, and Gatley found that star formation is taking place roughly uniformly throughout the central 3 kpc. This uniformity is likely to be the natural consequence of the widely distributed molecular material. Lester, Harvey, and Joy (1986) used the Kuiper Airborne Observatory and "superresolution" techniques to study the distribution of 100 μm emission from the center of the Whirlpool. *If* the dust temperature is very nearly constant throughout the core of the galaxy, they found what can be interpreted as a 3″ diameter ring of far-infrared emission located at about the same distance from the center as the ends of the spiral arms seen in CO, visual emission lines (e.g., Hua, Grundseth, and Nguyen-Trong 1987), and perhaps, 10 μm emission.

The stellar mass distribution in the center of M51 has been mapped at blue wavelengths by Feibelman (1979) and at very red visual wavelengths by Zaritsky and Lo (1986) and by Pierce (1986). This last author presented high-resolution images that show apparent concentrations of recent star formation distributed in a ring around the nucleus. This ring, if real, appears roughly coincident with the brightest points in the 10 μm scan of Telesco, Decher, and Gatley and has dimensions comparable to those estimated by Lester, Harvey, and Joy from their far-infrared data. The stars appear at longer wavelengths to be distributed in the shape of an oval or ellipse (Zaritsky and Lo 1986; Pierce 1986), with a position angle of $\sim 150°$ and ellipticity of 0.2 at an average brightness contour. Both values, however, change significantly as a function of brightness level, which has been interpreted as a consequence of a triaxial shape for the galaxy. At blue wavelengths, Feibelman (1979) found the position angles of the inner core also varied with radius from the nucleus of the galaxy, but these angles disagreed with those for the red contours. The difference may be due to different galaxian populations contributing at the very different wavelengths. Feibelman also presents a very useful schematic drawing of the inner 30″ region of the galaxy, which had not been well studied at that time. Because the stars dominate the gravitational potential of galaxies like M51, the significance of a nonaxisymmetric stellar mass distribution is that it creates nonradial forces on the gas. It is widely suggested that bars or ovals in the cores of galaxies contribute to enhanced star formation activity, resulting from a concentration of near galaxy centers.

Determination of the "true" stellar mass distribution dominates the mythology of near-infrared photometry and imaging, although relatively few authors have quantified stellar masses based solely upon J (1.25 μm), H (1.6 μm), or K (2.2 μm) data. For that reason, we have mapped the central 1′ of M51 in the three standard near-infrared bands and used the solar neighborhood as a model to estimate the stellar mass in the core of the Whirlpool using our observations. From this estimate, we deduce the average star formation rate since the galaxy was born, along with the rate, efficiency, and time scale of star formation.

We emphasize to the reader three guidelines or assumptions that govern the following analyses. First, with no other comment, we shall assume that widely used conversions between observational parameters and astrophysical quantities apply to M51. For example, although controversies over the conversion of $J = 1 \rightarrow 0$ CO line strengths to H_2 masses are important, they do not concern us here, except to serve as a warning about systematic uncertainties. Second, we shall assume that the processes and products of star formation dominate the emission at all wavelengths that we shall discuss.[1] Finally, we shall concentrate on the average properties of the central 50″ (2.3 kpc) of the galaxy, since this is the resolution of critical $J = 1 \rightarrow 0$ CO and far-infrared data. Furthermore, many of the higher resolution observations, such as our own that we report on here, cover a similar region and little more. Thus, where appropriate, we shall correct data to values equivalent to a 50″ circular region centered upon the nucleus. As noted above, there are interesting and important structures in the galaxy with sizes much less than the region over which we shall be calculating average values. We, therefore, caution readers against applying our derived values to any region smaller than $\sim 50''$.

II. THE OBSERVATIONS

The central region of M51 (NGC 5194) was observed during 1986 May and June using the 2.3 m telescope at the Wyoming Infrared Observatory (WIRO). We used the WIRO InSb radiometer described by Grasdalen, Hackwell, and Gehrz (1984), with standard near-infrared filters for the J (1.25 μm), H (1.6 μm), and K (2.2 μm) bands. A DC–coupled, integrating preamplifier was also used, obviating the need for a reference beam. The star HD 129653 was used for calibration, for which we took $J = 6.98$ (2.58 Jy), $H = 6.94$ (1.67 Jy), and $K = 6.98$ (1.10 Jy) (Elias *et al.* 1982). We estimate a total uncertainty of ± 0.15 mag for the maps, although this might be an underestimate for our H data.

We imaged a $64'' \times 64''$ area in all three passbands, using approximately a 6″ FWHM beam, which corresponds to a linear size of 280 pc at a distance of 9.6 Mpc for the galaxy. The

[1] For example, Allan Sandage has been recently quoted as stating "God lives at 100 μm" (Soifer, Houck, and Neugebauer 1987), which, if true, might seriously complicate our analysis of the far-infrared emission from M51.

images were obtained by scanning the secondary in declination and stepping the telescope in right ascension and were spatially oversampled by a factor of 6. During the image processing, the raw data were convolved with a 2″ FWHM Gaussian smoothing function. The resultant half-power size of the detector beam is 5″.2 × 7″.5, with the longer axis running northwest-southeast. The shape of the beam elongates the resultant images on small scale sizes, but not over large areas.

Contour maps of the central region of M51 in J, H, and K are presented in Figure 1, with the values of the iosphotes given in the caption. Where comparable with data from other workers (e.g., Telesco, Decher, and Gatley 1986), our results agree to within ~20%. To obtain as much detailed spatial information as our observations are capable, we used a maximum-entropy image-enhancement technique (Narayan and Nityananda 1986) on our H band data, which has the highest signal-to-noise ratio of our three maps. This map will allow us to compare the distribution of cool stars that dominate the near-infrared emission with other components of emission. The resulting contour map is presented in Figure 1d and an image is reproduced in Figure 2 (Plate 5). We estimate that the angular resolution of this image has about a factor of 2 increase over the unenhanced data.

As discussed in the Introduction, we wish to compare observed and derived quantities for the galaxy integrated over a 50″ diameter region centered on the nucleus. We detected emission over an area almost this size. However, we expect that a slight correction to our data is necessary to account for the emission at or below our noise level, but included within a hypothetical 50″ beam. We estimated this correction by plotting flux densities as a function of circular area on the images. We found a smooth variation between the two quantities, which we expect would continue to a large radius from the nucleus. However, for beam diameters larger than ~40″, there was a distinct "kink" as the flux density ceased to increase rapidly with larger area. Extrapolation of the smooth part of this curve to a 50″ diameter circular aperture centered on the nucleus suggests that integration of our images underestimates the actual flux density by ~20%; we thus increase the total near-infrared flux density that we derive for the entire area mapped by a factor of 1.2. Our estimated values for the flux density within a 50″ circular beam are presented in Table 1, along with the other parameters derived in the following sections.

III. ANALYSIS AND DISCUSSION

a) *Estimating Stellar Masses from Near-Infrared Observations*

The primary motivation for this project was to produce a widely applicable near-infrared mass-to-light ratio for normal galaxies. In the following three subsections we derive an expression that relates visual and near-infrared emission to the stellar mass, using the solar neighborhood as a model.

i) *A Model for the Stellar Mass Distribution in the Solar Neighborhood*

In the following discussion, we assume that the neighborhood of the Sun is a mixture of stars formed under a wide range of conditions, constantly and sedately over a Hubble time. It is a well-studied, nondescript portion of a late-type

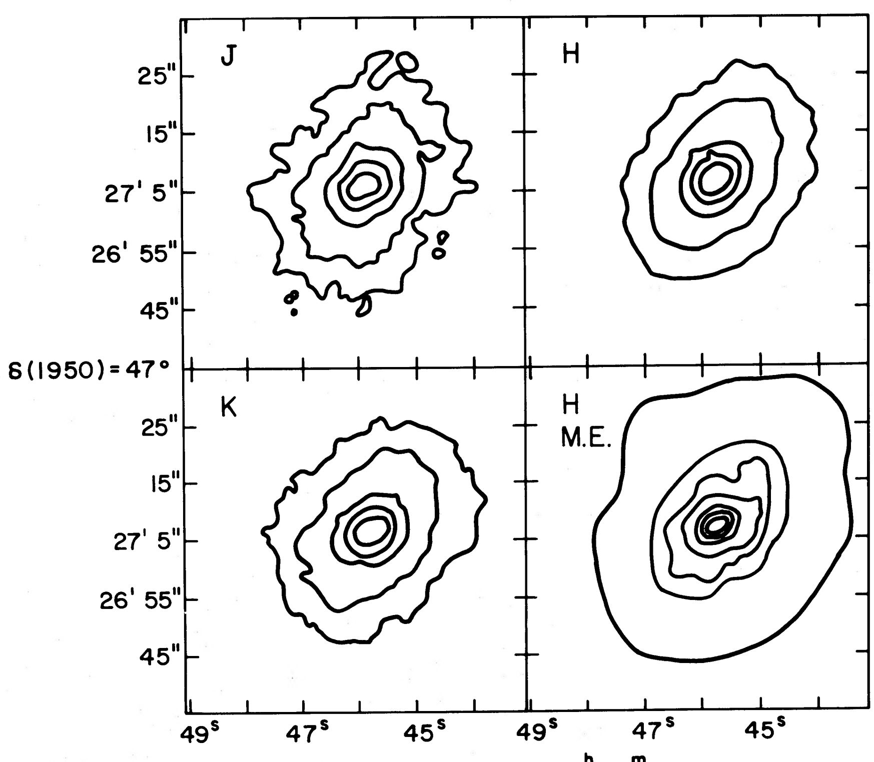

FIG. 1.—Three maps of the core of M51 obtained with a 6″ beam are shown: (a) J band, (b) H band, and (c) K band. In all cases the contours are 0.1, 0.2, 0.4, 0.6, and 0.8 of the peak. The peak is defined as 1.0 = 1.38 mJy arcsec^{-2} at J, 1.0 = 1.55 mJy arcsec^{-2} at H, and 1.0 = 1.50 mJy arcsec^{-2} at K. The 1 σ statistical noise level is ~0.03 mJy arcsec^{-2} for the H and K bands and ~0.05 mJy arcsec^{-2} for the J band. Shown in (d) is the H band image of the galaxy, enhanced using maximum entropy. The contour levels are 0.02, 0.1, 0.15, 0.2, 0.4, 0.6, and 0.8 of the peak and the 1 σ noise level is ~0.01 mJy arcsec^{-2}.

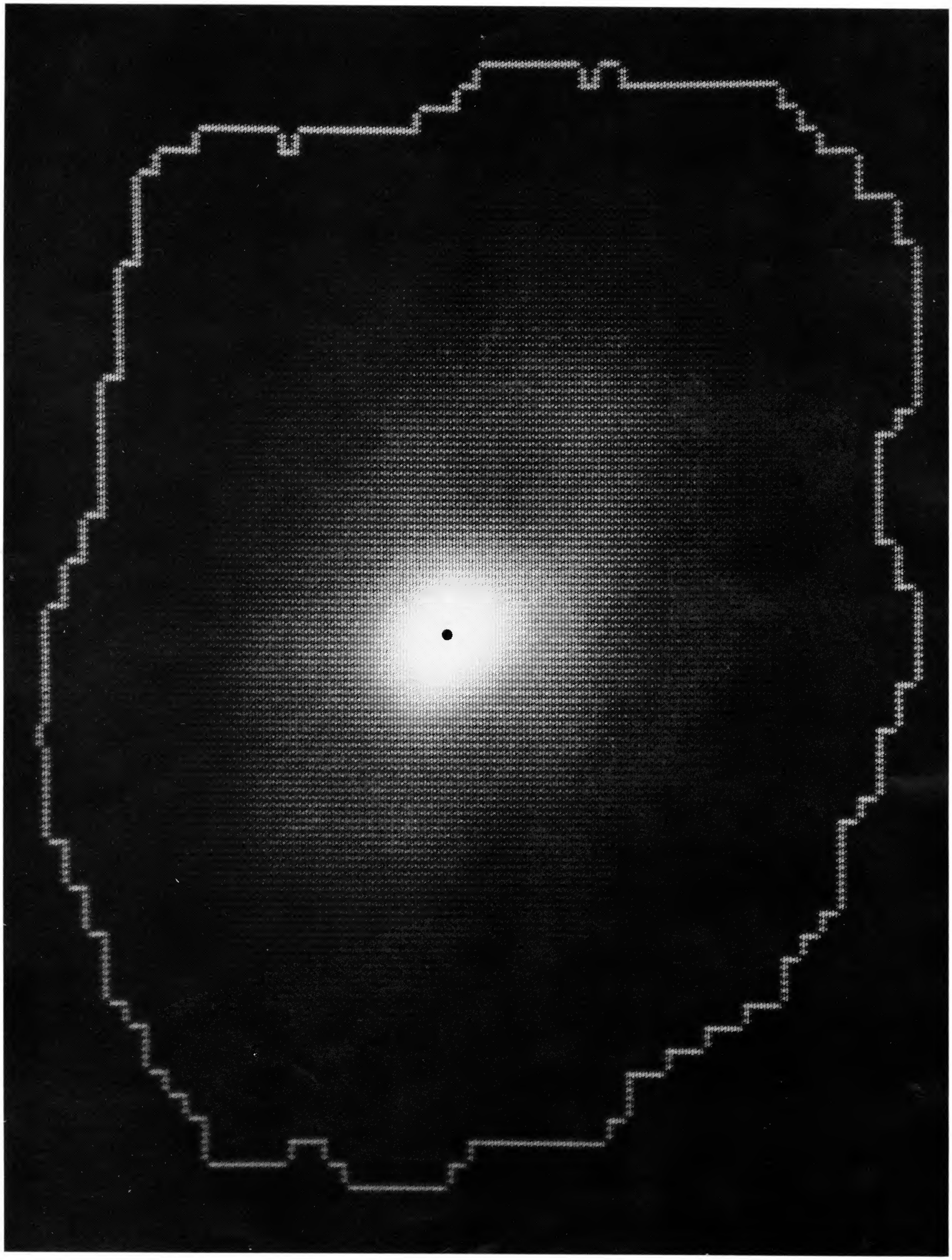

FIG. 2.—The H image of the central region of M51, enhanced using maximum entropy. The contour corresponds to the outer contour in Fig. 1d. North is up and east is to the left. The small dark dot marks the maximum of the 2.2 μm emission and has the position $\alpha(1950) = 13^h27^m45^s.77$, $\delta(1950) = 47°27'7''$, where both coordinates have an uncertainty of about $\pm 1''$ (1 σ rms). The full dimension of the figure is $53'' \times 61''$ (east-west $\times$ north-south).

THRONSON AND GREENHOUSE (*see* **327**, 673)

TABLE 1

THE 2.3 kpc (50″) CENTER OF M51

Near-infrared flux density[a]	$F_J = 0.51$ Jy, $m_J = 8.79$ $F_H = 0.50$ Jy, $m_H = 8.29$ $F_K = 0.53$ Jy, $m_K = 7.81$
Distance	9.6 Mpc
Infrared luminosity (L_{IR})[b]	$6 \times 10^9\ L_\odot$
Integrated CO line strength (I_{CO})[c]	31.1 K km s^{-1}
Molecular gas mass (M_{H_2})[d]	$8 \times 10^8\ M_\odot$
Atomic gas mass ($M_{H\,I}$)[e]	$\leq 1.6 \times 10^7\ M_\odot$
Mass of "old" stars ($M_{*,\mathrm{old}}$)[f]	$1.2 \times 10^{10}\ M_\odot$
Mass of currently-forming stars ($M_{*,\mathrm{young}}$)[g]	$7.8 \times 10^6\ M_\odot$
Current rate of star formation ($\dot{M}_{*,\mathrm{young}}$)[h]	$3.9\ M_\odot$ yr^{-1}
Recent rate of star formation[i]	$0.8\ M_\odot$ yr^{-1}
Average rate of star formation ($\dot{M}_{*,\mathrm{old}}$)[j]	$0.8\ M_\odot$ yr^{-1}
Efficiency of star formation[k]	0.01
Gas fraction[l]	0.07
Depletion time[m]	2×10^8 yr

[a] This work, § II. Estimated total uncertainty, ±20%.
[b] Telesco and Harper 1980; Smith 1982.
[c] Scoville and Young 1983.
[d] This work, § IIIc.
[e] Estimated from large-beam data of Weliachew and Gottesmann (1973).
[f] This work, § IIIc.
[g] Salpeter IMF, 0.1 → 100 $M_\odot$. This work, § IIIc.
[h] Salpeter IMF, 0.1 → 100 $M_\odot$. This work, § IIIc.
[i] Averaged over the past billion years. This work, § IIIc.
[j] Averaged over a Hubble time. This work, § IIIc.
[k] $M_{*,\mathrm{young}}/M_{H_2}$. This work, § III*d*.
[l] $M_{H_2}/M_{*,\mathrm{old}}$. This work, § IIIc.
[m] $M_{H_2}/\dot{M}_{*,\mathrm{young}}$. This work, § III*b*(iv).

spiral galaxy. The emission from the stars in our part of the Milky Way should, therefore, be representative of other regions in which star formation has been continuing for a long period of time and in which stars have been produced from a wide range of physical conditions. Of course, we have no way of knowing the full range of conditions under which the local stars have formed, and we must assume that these stars are the product of a representative mixture of star-forming regions. Stating our goal concisely, we are adopting the solar neighborhood as a reasonable model for the product of long term star formation in galaxies.

Determinations of the local stellar number density were recently summarized by Robin and Crézé (1986), which we adopt to find the local stellar brightness. A simple, older model for the number density is presented in Allen (1973) which is roughly similar to the more detailed and complete model of Robin and Crézé. Both models give comparable results for the following analysis. The stellar number density that we have adopted includes no late-type stars with $M_v \leq -2.0$ ($M_K \leq -7$). Thus, the extremely luminous M supergiants and asymptotic giant-branch stars are not included in our model. These stars are extremely rare in the solar neighborhood and, we expect, in regions to which we apply our analysis. Supergiants are often suspected to make a significant contribution to the near-infrared light in energetic star-forming regions, such as the central regions of M51, but contribute almost no mass. This idea is questionable and by no means established: Bothun *et al.* (1985) discuss a series of models and observations in which AGB and supergiant stars contribute only several percent of the near-infrared light in systems that have been forming stars for a long time. Furthermore, Garwood and Jones (1987) recently modeled the distribution of near-infrared light in the Milky Way and, for the local neighborhood, found that the extremely luminous red supergiants contributed about as much light at these wavelengths as do young, main-sequence stars, only about several percent. We assume that this condition also applies to the core of M51. However, it is possible that our ignorance of the relative emission from AGB stars and supergiants is a major uncertainty in the following analysis.

ii) *Stellar Emission in the Solar Neighborhood*

We converted *V* magnitudes into *J*, *H*, and *K* magnitudes using the colors versus spectral type and luminosity class in Johnson (1966) and Frogel *et al.* (1978). Contribution to the total light of the local neighborhood from three luminosity classes and the local volume brightness of the Milky Way in four passbands were then determined. The results are presented in Table 2, where the brightness in janskys and in magnitudes is listed. It is our belief that, because *H* magnitudes have been less frequently quoted in the literature for stars with reliable spectral types, results for this band are more uncertain than those for either *J* or *K*.

Not surprisingly, our adopted model shows that the cool, luminous giant stars dominate the emission at wavelengths longward of ~1 μm, although there is a nonnegligible contribution from this luminosity class in bands as short as *V*. Uncertainties in the amount of light from giants is one of the limitations of using the near-infrared to map the stellar mass distribution, since giant stars are rare and, thus, make only a small contribution to the mass of stars. Like other workers in this field, we must assume that, although uncommon, giants are distributed similarly to the general stellar population. Furthermore, we must assume that their relative contribution to the near-infrared light is constant throughout any region that we might map. That is, the relative numbers of giants and dwarfs do not change with position in the central 2.3 kpc of M51. These points are discussed more fully in the following section.

Main-sequence stars make a modest contribution in all the near-infrared bands and dominate the light in *V*. To illustrate the relative amount of light from dwarf stars of different spectral types, we present Figure 3, where we have plotted the cumulative contribution from stars of different spectral types to the integrated flux in each of three passbands. All three curves drop steeply for spectral types earlier than early B, as very few such short-lived stars are found in the solar neighborhood. Such stars are, of course, expected to be much more common in active star-forming regions, but, judging from the figure, we would guess that they contribute only modestly to the light at near-infrared wavelengths, except under conditions of extraordinarily high rates of star formation.

TABLE 2

CONTRIBUTION TO LIGHT IN THE SOLAR NEIGHBORHOOD[a]

	V	*J*	*H*	*K*
Giants (percent)	16	57	63	72
Subgiants (percent)	6	6	7	3
Dwarfs (percent)	78	37	30	25
Flux density (Jy pc^{-3})	2.1	2.6	2.8	2.3
Brightness (mag pc^{-3})[b]	8.2	7.0	6.4	6.2

[a] Adopted magnitude normalization: $V = 0.0$ for $F_V = 3800$ Jy, $J = 0.0$ for $F_J = 1600$ Jy, $H = 0.0$ for $F_H = 1000$ Jy, and $K = 0.0$ for $F_K = 680$ Jy.
[b] Solar neighborhood colors: $V-K = 2.0$, $H-K = 0.2$, and $J-H = 0.6$.

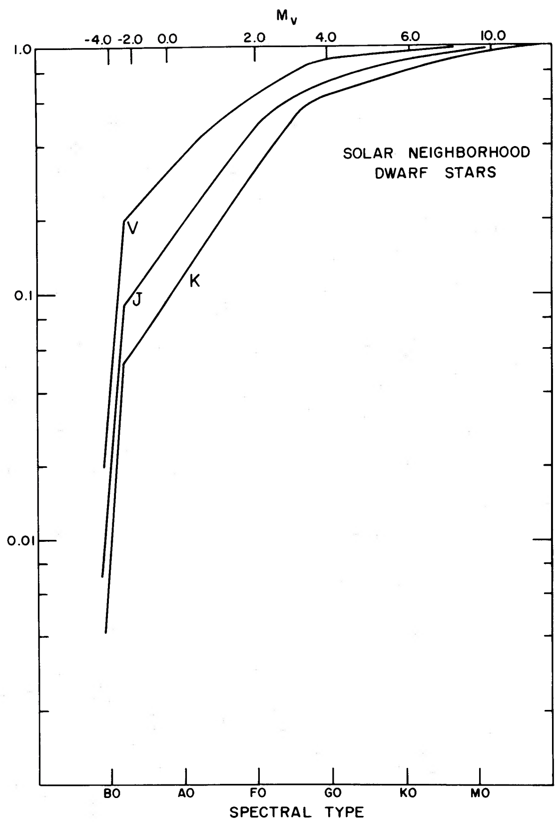

FIG. 3.—The cumulative contribution of stars of different spectral types to the total light from solar neighborhood dwarf stars. Table 1 gives the percentage contribution to the light in four standard bands from three luminosity classes, including the dwarfs. Note that the magnitude scale at the top of the figure is only approximate, as there can be a wide range of magnitudes for main-sequence stars of a single spectral type.

Figure 3 and Table 2 show clearly that V is a good band for estimating a total stellar mass, due to the large fractional contribution from the dwarf stars, which contain most of the stellar mass. However, V band observations are very susceptible to interstellar extinction and to contamination by emission from small numbers of young, early-type stars. However, in regions of low obscuration and low rates of star formation, visual-wavelength observations are probably very reliable for estimating the total stellar mass. In the Appendix, we discuss the different definitions of broad-band luminosity that are presently in use.

Uncertainties in the contribution of O, B, and A stars to the emission from composite systems can be significant at wavelengths as long as J (1.25 μm). At K (2.2 μm), 30% of the light contributed by dwarfs ($\sim$8% of the total) is from O, B, and A stars, and at 1.2 μm, these stars contribute $\sim$18% to the total light. For comparison, Telesco and Gatley (1984) found that early-type stars contributed 10%–20% of the near-infrared light from the center of the very energetic, peculiar Sbc galaxy NGC 3310. Thus, a contribution of several percent is a significant fraction for our location in the Milky Way, a region that is not dominated by extremely energetic, on-going star formation. In terms of integrated near-infrared emission, these fractional contributions may not be particularly large, but near-infrared colors (e.g., H–K) can be significantly affected by the presence of an early population (e.g., Telesco and Gatley). Furthermore, near-infrared imaging must be interpreted with care, based upon our Figure 3 and Table 2. Thus, a warning: since the young stars contribute between $\sim$10% and $\sim$20% of the light in these bands, modest variations in the near-infrared brightness of a star-forming galaxy might very well reflect variations in the numbers of young stars, rather than numbers of old stars. We guess that structures in the near-infrared brightness that ranges over factors of 2 or 3 or more are the result of true variations in the underlying old stellar population, but brightness changes of 50% or less might be due to contributions from early-type stars. Multicolor mapping of an object should reduce the uncertainties in the source of the near-infrared light considerably.

iii) *A Near-Infrared Mass-to-Light Ratio*

Bahcall (1984) recently summarized the various estimates for the local mass density of stars, with a typical value being 0.06 $M_\odot$ pc^{-3} (see Limber [1959] for a good discussion of this type of determination). From Table 2, we thus calculate the following mass-to-light relation at K,

$$M_{*,\mathrm{old}}(M_\odot) = 2.6 \times 10^8 D^2(\mathrm{Mpc})\, F_K\,(\mathrm{Jy})\,, \qquad (1)$$

where the coefficient changes very little as a function of band: 2.9×10^8, 2.3×10^8, or 2.1×10^8 for V, J, or H band observations, respectively.

It seems clear that this formulation should produce very reasonable estimates for the mass of stars in the disk of a spiral galaxy, since it was derived for exactly that type of region in the Milky Way. If star formation has been constant for a long period of time, we expect that equation (1) can also produce a good estimate of the stellar mass in other locations in a galaxy. We have tested this hypothesis. For example, Thronson *et al.* (1988) estimated the stellar mass in the Magellanic irregular galaxy NGC 4214 using this equation and their near-infrared map. The calculated value was midway in the range of stellar masses determined from visual-wavelength photometry. More appropriate to this paper, Scoville *et al.* (1985) investigated the inner several kpc of the bright spiral NGC 253. As part of their study, they plotted the dynamical mass as a function of position, determined from the rotation curve of the galaxy, along with the 2 μm flux (their Fig. 9). Equation (1) gives agreement between the near-infrared brightness and the calculated dyamical mass to within a factor of 2 from radii 0.5–6 kpc in NGC 253, which is entirely satisfactory. Our light-to-mass conversion also produces good agreement with results from rotation-curve data on the central region of the lethargic, early-type spiral galaxy M31. The velocity structure in the core of M31 has been studied by Rubin and Ford (1971) and Rubin, Ford, and Kumar (1973). Using the large-beam H and K photometry of Sandage, Becklin, and Neugebauer (1969), Aaronson, Mould, and Huchra (1980), and Persson *et al.* (1980), we use equation (1) to estimate a stellar mass that is within a factor of 2 of that determined by assuming Keplerian orbits in the center of the galaxy.

Recently, Devereux, Becklin, and Scoville (1987) surveyed near-infrared emission from the nuclei of a large number of normal galaxies of all major morphological types. Their beam sizes corresponded to a few hundred parsecs at the distances of the galaxies, about an order of magnitude smaller than the region we are investigating in M51. They estimated nuclear masses using line widths and found, significantly, that there was no evidence for systematic deviations among the Hubble types from a single value for the mass-to-light ratio at 1.6 μm. The coefficient found by Devereux, Becklin, and Scoville is only 10% larger than that which we derived above for the solar neighborhood. It may be, as Devereux, Becklin, and Scoville and others have suggested, that the giants that contribute so much light in the near-infrared are produced by low-to moderate-mass main-sequence stars. This is certainly the case for the local solar neighborhood model that we took from Robin and Crézé (1986), which has the turnoff to the giant branch at a position on the main sequence appropriate to stars of $\sim 1\ M_{\odot}$. These dwarf stars would, in turn, be expected to dominate the total visible mass for a wide variety of galaxies.

b) The Central Region of M51

i) *General Description of the Near-Infrared Images*

The images of M51 at all three near-infrared wavelengths are very similar over the region mapped. Indeeed, detailed comparison of the brightness distribution shows no difference in shape or structure that could not be ascribed to statistical noise in the original data. Thus, the near-infrared colors of the galaxy do not vary with position over the brighter regions that we mapped. Of course, significant color variations are possible in the less bright regions that are included in our maps. To the degree that the near-infrared colors are sensitive to the composition of an older stellar population, that composition shows no significant variation over about the inner 2 kpc diameter region in M51. Consequently, we argue that the processes of star formation that have taken place in the center of this galaxy have produced very similar stellar populations over a large area. We note, however, that much of the interesting structure in this part of M51, such as the spiral arms, does not extend into the region that we mapped with high signal-to-noise ratio.

The near-infrared colors of the nucleus are consistent with emission dominated by late-type giants. Telesco and Gatley (1984), for example, presented near-infrared two-color diagrams in which the potential contribution from a variety of components is shown. Based upon these diagrams and the uniformity of color over the region that we mapped, the near-infrared emission from M51 does not appear to be strongly contaminated by hot dust or blue stars in emission or affected by significant amounts of extinction at these wavelengths. Thus, the brightness distribution in our maps should be a good representation of the distribution of late-type giants and, presumably, the total stellar mass, as discussed in previous sections.

A number of other authors have discussed the elongated, oval shape of the central core of M51. It seems to have first been discussed by Feibelman (1979). Kent (1984) produced a large study of ellipticity in galaxies, while Zaritsky and Lo (1986) found that elliptical brightness distributions were quite common in 0.8 μm images of a small sample of 11 spirals, including M51. Zaritsky and Lo also estimated the magnitude of the nonradial force in M51, which is expected to result from a nonspherical mass distribution. Furthermore, these authors found that the central light distribution of M51 had a definite "isophotal twist." That is, the position angle of the elliptical contours varied as a function of contour level. The interpretation of this "twist" is that such objects may not possess an axis of rotational symmetry and may be triaxial in shape. The "twist" is not obvious in our data, although our figures are consistent with the description of the red-light distribution given by Zaritsky and Lo. The more detailed red images of Pierce (1986) look very much like our Figure 1.

We find no clear sign of spiral structure in our raw images (Figs. 1*a*–1*c*), although arms are known to extend somewhat into the region that we mapped, $\sim 20''$ from the nucleus (see the 10 μm scans in Telesco, Decher, and Gatley [1986], the visual-wavelength images in Feibelman [1979] and Pierce [1986]; and the CO maps in Lo *et al* [1987]). Since spiral arms are generally blue in color, it is not surprising that they do not distinctly appear in our data. However, it is quite likely that the lower signal-to-noise ratio in the outer part of our images masks any contribution to the light from the arms. On the other hand, our *H* band image enhanced via maximum entropy, Figures 1*d* and 2, cleary shows an apparent "hook" or "ridge" in emission close to the location where the spiral arms merge with the bright central emission at visual wavelengths (position angles of $\sim 155°$ and 330°).

ii) *The Stellar and Gas Mass in the Core of M51 and the Star Formation Rate Averaged over a Hubble Time*

With the tools to effectively analyze the near-infrared data, we shall now discuss the history and present conditions of star formation in the core of M51. Where we find it interesting, we shall compare the results for the central regions with those derived for the entire galaxy. Parameters derived from our analysis are presented in Table 1.

From equation (1) and the *K* brightness in Table 1, the total stellar mass in the central 2.3 kpc of M51, $M_{*,\rm old}$, is $\sim 1.2 \times 10^{10}\ M_{\odot}$. This value is nearly identical to that obtained from the visual and CO rotation curves (Burbidge and Burbidge 1964; Scoville and Young 1983). Thus, $\sim 10\%$ of the total mass of the galaxy is within the 2.3 kpc region that we are studying here (Scoville and Young 1983), although the same region is by far the brightest at all wavelengths, in particular contributing one-third of the far-infrared luminosity of the entire galaxy (Smith 1982).

M51 is a bright far-infrared and radio continuum source, and we assume that star formation has been going on at some rate near the center of the galaxy since it was formed. If we take a Hubble time to be $\tau_{\rm H} = 1.5 \times 10^{10}$ yr, star formation at a rate of $\dot{M}_{*,\rm old} = 0.8\ M_{\odot}\ \rm yr^{-1}$ averaged over that time would be sufficient to produce the observed mass of old stars that we calculate from our near-infrared data. Based upon a conventional view of galaxian formation, a period of intense star formation early in the history of M51 would presumably produce a massive core of stars. Thus, many of the stars whose distribution is shown in Figures 1 and 2 are as old as the galaxy. However, with as much interstellar gas as M51 possesses (Weliachew and Gottesmann 1973; Scoville and Young 1983), we think it likely that star formation has been a continuous process since the galaxy was born. Thus, our calculated average rate of star formation over a Hubble time, 0.8 $M_{\odot}$ yr^{-1}, may be an upper limit, but perhaps not by much.

The blue luminosity may be used to estimate the star formation rate averaged over about the past billion years (Kennicutt 1983; Gallagher, Hunter, and Tutukov 1984; Thronson and Telesco 1986) for comparison with the star formation rate derived for a Hubble time. Palumbo *et al.* (1985) estimated $M_B = -16.9$, or $L_B = 1.3 \times 10^8\ L_{\odot}$ for approximately the central 50″ of the galaxy (see Appendix). Using the relation between average star formation rate and blue luminosity derived by Thronson and Telesco, we estimate $\dot{M} = 0.8\ M_{\odot}$ yr^{-1} over the past billion years, identical to that derived from the near-infrared data for the rate averaged over a Hubble time. Keeping in mind the systematic uncertainties in this type of calculation, we estimate that the star formation rate, averaged over long periods of time, is in the range 0.5–1 $M_{\odot}$ yr^{-1} for the central 2.3 kpc of the Whirlpool.

Millimeter-wave $J = 1 \rightarrow 0$ CO line emission is currently widely used to estimate the molecular mass in galaxies (see the analyses of Dickman, Snell, and Schloerb [1986] and Maloney and Black [1987]). For the central 50″ of M51, Scoville and Young find $M_{H_2} = 8 \times 10^8\ M_\odot$, at least 40 times greater than the mass of atomic gas (Weliachew and Gottesmann 1973). There may be substantial systematic uncertainties to the technique used by Scoville and Young to estimate the molecular mass, but Thronson *et al.* (1987) marginally detected 1.3 mm continuum dust emission from M51 at a level consistent with the mass of H_2 derived by Scoville and Young. With the stellar mass determined from the near-infrared data above, the fractional mass of H_2 in the core of the Whirlpool is 7%.

iii) *The Efficiency and Rate of Star Formation*

The present rate of star formation may be estimated from many tracers of ongoing star formation, but we shall use the far-infrared luminosity, primarily because we are more familiar with its uncertainties.

Thronson and Telesco (1986) assumed that stars were forming continuously or, equivalently, that a "burst" of star formation lasted much longer than the lifetime of the massive stars that dominate the far-infrared emission. They found $\dot{M}_{OBA}(M_\odot\ yr^{-1}) = 2.1 \times 10^{-10} L_{IR}(L_\odot)$ for O, B, and A stars only. The coefficient in the relation would be a factor of 3 higher if stars in the mass range 0.1–100 $M_\odot$ form, rather than just O, B, and A stars. With no evidence to the contrary, we assume that the wider range of masses are born in the galaxy. With an infrared luminosity of $6 \times 10^9\ L_\odot$ for the central 50″ of M51 (Smith 1982), the current rate of star formation, $\dot{M}_{*,young}$, is $\sim 4\ M_\odot\ yr^{-1}$, which is close to values estimated for the entire Milky Way (e.g., Scoville and Sanders 1987).

A currently popular idea is that only early-type stars form under some conditions in galaxies, in which case the star formation rate derived from the far-infrared luminosity is $\dot{M}_{*,young} = 0.5\text{–}1.3\ M_\odot\ yr^{-1}$. This rate is nearly identical to that calculated in the previous section as the average over a Hubble time, but the agreement must be happenstance. Because of their short lifetimes and small numbers, creation of only O, B, and A stars will not produce large numbers of long-lived, cool stars, which appear to dominate the near-infrared emission. We assume that star formation is a purely local process in most environments, in which the range of stellar masses that form is not strongly governed by the type of galaxy in which they formed. Rather, the range is limited only by fundamental physical laws to 0.1–100 $M_\odot$. We also assume that the core of M51 is producing a wide range of stellar masses and that a formation rate of 4 $M_\odot\ yr^{-1}$ is probably a reliable estimate.

Thronson and Telesco (1986) derived a stellar mass-to-luminosity ratio for newly formed stars, $1.3 \times 10^{-3}\ M_\odot\ L_\odot^{-1}$, which allows us to estimate the mass of stars that have recently formed. A Salpeter function and stellar mass range of 0.1–100 $M_\odot$ was assumed to find this ratio. For a far-infrared luminosity of $6 \times 10^9\ L_\odot$, the mass of new stars is thus $7.8 \times 10^6\ M_\odot$. This is an extremely small fraction of the total mass of stars in the galaxy's central region that we are studying here, not surprisingly, but it is 1% of the molecular gas mass (Table 1). We interpret this percentage as the instantaneous efficiency of star formation for this region of the galaxy, and it is a value that is quite comparable to that found over large areas in other galaxies. Since the mass fraction of gas in spiral galaxies is at most only several percent, the *long-term* efficiency of star formation must be very high. On a small scale, higher efficiencies are also possible, but on large scales it appears likely that, once again, fundamental physical processes work to set limits to the efficiency. Thus, the bright far-infrared emission from the core of M51 is not due to a particularly efficient mechanism of star formation, but rather to the effective accumulation of star-forming gas.

The star formation efficiency for the entire galaxy can also be estimated using its total far-infrared luminosity, $2 \times 10^{10}\ L_\odot$ (Smith 1982) and its moleular mass, $9 \times 10^9\ M_\odot$ (Scoville and Young 1983). Using the same assumptions as above, the global efficiency is 0.3%, modestly lower than that found for the core. This difference may be due to uncertainties in the observations, deriving a stellar mass from the infrared luminosity, or estimating the molecular gas mass using CO line observations. More interestingly, it is possible that the initial mass function is different in the disk of the galaxy, which contributes about two-thirds of the total infrared luminosity. We do not, however, consider the factor of 3 difference between the efficiency calculated for the core and for the nucleus to be significant, considering the systematic uncertainties of this type of calculation. Furthermore, a number of authors (e.g., Cox and Mezger 1987, Persson and Helou 1987) have recently discussed the sources of far-infrared emission in galaxies and have warned that emission from inert regions ("infrared cirrus") can contribute significantly to the luminosity at far-infrared wavelengths. Thus, our estimate of the efficiency of star formation for the entire galaxy might be too high. We do not believe this to be the case in the core of M51, due to its very high concentration of molecular material relative to atomic gas.

iv) *Enhanced Star Formation in the Core of M51: Limiting Mechanisms and the Periodicity of "Bursts"*

The core of M51 presently has a rate of star formation higher than that averaged over a Hubble time, which is often presently referred to as a "starburst." Since this rate has apparently not been maintained for a long period of time, we think it likely that depletion of gas is a likely limit to the persistence of the present high rate of star formation. At the calculated rate of 4 $M_\odot\ yr^{-1}$, the observed gas mass (Table 1) will last $\sim 2 \times 10^8$ yr, over which time the presently observed stellar mass will increase by $\sim$5–7%, depending upon the fraction of gas returned to the interstellar medium (ISM) by evolved stars. Return of gas to the ISM will not significantly alter the estimated time scale, since most of the gaseous material remains locked up in the low-mass stars that we assume to be forming in abundance. Of course, it is likely that star formation may not ultimately consume all the available gas found in the core of the galaxy. Furthermore, most of the gas from which high-mass stars are formed is returned in a short time to the ISM. Thus, it is possible that both the time scale for depletion of gas and the percentage increase of the stellar mass are upper limits.

For many galaxies, it has been suggested that supernovae, a direct consequence of the formation of large numbers of stars, may expel interstellar gas from an active region (e.g., Mathews and Baker 1971; Sanders 1981; Heckman, Armus, and Miley 1987). This would be an effective mechanism to limit the formation of new stars and it can be shown that it is possible on a time scale comparable to that estimated above for depletion due to star formation. Detailed models of the effect of supernovae on star-forming gas have recently been presented (Tenorio-Tagle, Bodenheimer, and Yorke 1985) and a rate of cloud disruption of a few hundred solar masses per supernova has been estimated. We estimate the supernova rate in the central region of M51 by, once again, using the Milky Way as a model, For our galaxy, van den Bergh (1987) estimates a rate of $\sim 0.02\ yr^{-1}$. If stars are formed at 5 $M_{\odot}\ yr^{-1}$ in the Milky Way (summary by Scoville and Sanders [1987]), the supernova rate as a function of star formation rate is $\sim 0.004\mathfrak{R}\ yr^{-1}$, where $\mathfrak{R}$ is the star formation rate. If the conditions in the central 2.3 kpc of M15 (Table 1) are similar to those that apply on average to the Milky Way and if gas is expelled from the core at a rate of 300 $M_{\odot}$ per supernova, this gas will be lost to the core in $\sim 10^8$ yr, which is comparable to the time scale of depletion by stellar creation.

Thus, we conclude that there are two mechanims that are working to limit the length of time over which star formation at the present rate can be maintained in the core of M51: the depletion of the star-forming gas and/or the expulsion of gas from the galaxian core. General arguments for both mechanisms put the time scale for a high rate of star formation as $\sim 10^8$ yr.

If the characteristics that we have estimated for the present period of enhanced star formation (rates, time scales, etc.) are typical of past bursts, if they occurred, a stellar mass equivalent to the total that we find in the core of M51 would have been formed in 20–30 such bursts, each lasting $\sim 10^8$ yr and producing $\sim 4\ M_{\odot}\ yr^{-1}$. We adopt the conventional view that, in fact, a large fraction of the presently observed stellar mass was formed in a very early period of intense star formation. In this case, the more recently formed stars would have been formed in a handful of "starbursts," say 5 or 10. In this situation, the core of the galaxy would have to be "bursting" only $\sim 5\%$ of the time. The remaining 95% of the time would presumably be a period of accumulation of gas, as if in preparation for another "burst," with relatively little star formation taking place. During the lethargic period, gas would presumably fall into the core of the galaxy and be warmed by the general interstellar radiation field and by kinetic energy acquired as part of the process of infall. Star formation may not begin in earnest in the center of M51 until there is sufficient gas so that, say, the volume density is high enough and gravitational contraction can overcome the kinetic energy acquired by the processes of gas accumulation. The special conditions in the nucleus of the galaxy suppress star formation for long periods until the amount of molecular material overwhelms the forces that would restrain the birth of new stars.

IV. SUMMARY

We have derived a near-infrared mass-to-light ratio for galaxies, using the local solar neighborhood as a model and applied it to *J*, *H*, and *K* images of the central 2.3 kpc of the Whirlpool (M51, NGC 5194). Comparison with stellar masses determined primarily from rotation curves shows good agreement. We believe that this agreement is a consequence of the domination of near-infrared light by low- to moderate-mass red giants, which should effectively trace the location and abundance of low-mass main-sequence stars. Our derived mass-to-light ratio may be applicable to a wide variety of galaxies.

We find that the near-infrared appearance of M51 is nearly identical in all three passbands, with a distinct elliptical shape. The center of the galaxy may be a triaxial ellipsoid, producing a significant nonradial force on material in its vicinity. From far-infrared photometry, we estimate that the present star formation rate in the central 2.3 kpc of the galaxy is $\sim 4\ M_{\odot}\ yr^{-1}$, if the Salpeter function from 0.1 to 100 $M_{\odot}$ is a fair representation of the initial mass function of young stars. Using the CO line observations, we estimate that the instantaneous efficiency of star formation is close to 1%, similar to values found for the disk of the galaxy. We conclude that, although the center of M51 is quite bright over a wide range of wavelengths, star formation is proceeding quite normally. There is a great deal of molecular mass in this region of the galaxy, leading to a high rate of star formation. Either the depletion or the expulsion of the gas can bring star formation to a halt within $\sim 10^8$ yr, by which time the stellar mass in the core will have increased by roughly 5%.

By concentrating upon the near-infrared emission and star formation, as we have done here, we have ignored what is probably the most important process in enhanced or "bursting" star formation: the unusual accumulation of large amounts of molecular gas.

We appreciate useful discussions and/or data in advance of publication from K. Y. Lo and C. M. Telesco. This work was supported in part by NASA grant NAG 2-134.

APPENDIX

THE BLUE LUMINOSITY OF GALAXIES

One of the most curious developments in galaxy photometry in recent years has been the proliferation of definitions of luminosity. It is this kind of thing that gives fits to the uninitiated and we briefly describe each system here. In part this is a service to the reader, but, more usefully, *we* need a reference that we can quickly look up when we have to wade into photometric observations in the future. The following discussion refers primarily to blue luminosity, since until the *IRAS* program this was the wavelength of most of the photometry of galaxies. We note that one of the more frustrating consequences of the baroque systems of luminosity is that in many analyses of galactic emission, different definitions are used in the same paper. This seems to be most common with the second definition.

Probably the least-used system of blue luminosity is the one that we have adopted in this paper and the one that we think makes the most sense. It is the amount of radiation through the standard Johnson-Morgan *B* (or some other) filter, with $1\ L_{\odot} \equiv 3.9 \times 10^{33}$ ergs s^{-1}. In this system, the blue luminosity of the Sun is $\sim 0.14\ L_{\odot}$.

The most commonly used definition of blue luminosity is, in fact, how many times more luminous in the *B* band is an object than the Sun, adopting a *B* magnitude of, typically, $m_{B,\odot} = 5.48$. By definition, the blue luminosity of the Sun in this system is $1\ L_{\odot}$, but therefore $1\ L_{\odot} \approx 0.53 \times 10^{33}$ erg s^{-1}.

The most recent contribution to the variety of broad-band luminosity seems to have been a product of the analysis of *IRAS* data, in which νF_ν (or λF_λ) has evolved into a luminosity. Although νF_ν has the proper units, it is not a luminosity as usually conceived and, perhaps, should be referred to a *monochromatic* luminosity (if such a thing is possible). In any case, if 1 $L_\odot = 3.9 \times 10^{33}$ ergs s^{-1} in this system, the blue luminosity of the Sun is about 0.62 $L_\odot$.

REFERENCES

Aaronson, M., Mould, J., and Huchra, J. 1980, *Ap. J.*, **237**, 655.
Allen, C. W. 1973, *Astrophysical Quantities* (London: University of London Press), p. 246.
Ambartsumian, V. A. 1958, in *La Structure et L'Evolution de L'Univers*, ed. R. Stoops (Brussels: Institute International de Physique Solvay), p. 241.
Bahcall, J. 1984, *Ap. J.*, **276**, 169.
Bothun, G. D., Mould, J., Schommer, R. A., and Aaronson, M. 1985, *Ap. J.*, **291**, 586.
Burbidge, E. M., and Burbidge, G. R. 1962, *Ap. J.*, **135**, 694.
———. 1964, *Ap. J.*, **101**, 101.
Cox, P., and Mezger, P. 1987, in *Star Formation in Galaxies*, ed. C. J. L. Persson NASA Conf. Pub. 2466, p. 23.
Devereux, N. A., Becklin, E. E., and Scoville, N. 1987, *Ap. J.*, **312**, 529.
Dickman, R. L., Snell, R. L., and Schloerb, F. P. 1986, *Ap. J.*, **309**, 326.
Elias, J. H., Frogel, J. H., Matthews, K., and Neugebauer, G. 1982, *A.J.*, **87**, 1029.
Feibelman, W. A. 1979, *A.J.*, **84**, 497.
Frogel, J. A., Persson, S. E., Aaronson, M., and Matthews, K. 1978, *Ap. J.*, **220**, 75.
Gallagher, J. S., Hunter, D. A., and Tutukov, A. V. 1984, *Ap. J.*, **284**, 544.
Garwood, R., and Jones, T. J. 1987, *Pub. A.S.P.*, **99**, 453.
Grasdalen, G. L., Hackwell, J. A., and Gehrz, R. D. 1984, *Pub. A.S.P*, **96**, 1017.
Heckman, T. M., Armus, L., and Miley, G. K. 1987, *A.J.*, **92**, 276.
Hua, C. T., Grundseth, B., and Nguyen-Trong, T. 1987, *Ap. Letters Comm.*, **25**, 187.
Johnson, H. L. 1966, *Ann. Rev. Astr. Ap.*, **4**, 193.
Kennicutt, R. C. 1983, *Ap. J.*, **272**, 54.
Kent, S. 1984, *Ap. J. Suppl.*, **56**, 105.
Lester, D. F., Harvey, P. M., and Joy, M. 1986, *Ap. J.*, **302**, 280.
Limber, D. N. 1959, *Ap. J.*, **131**, 168.
Lo, K. Y., Ball, R., Masson, C. R., Philips, T. G., Scott, S., and Woody, D. P. 1987, *Ap. J. (Letters)*, **317**, L63.
Maloney, P., and Black, J. 1987, *Ap. J.*, in press.
Mathews, W. G., and Baker, J. C. 1971, *Ap. J.*, **170**, 241.
Morgan, W. W., and Osterbrock, D. E. 1969, *A.J.*, **74**, 515.
Narayan, R., and Nityananda, R. 1986, *Ann. Rev. Astr. Ap.*, **24**, 127.
Palumbo, G. G. C., Fabbiano, G., Fransson, C., and Trinchieri, G. 1985, *Ap. J.*, **298**, 259.
Peimbert, M. 1968, *Ap. J.*, **154**, 33.
Persson, C. J. L., and Helou, G. 1987, *Ap. J.*, **314**, 513.
Persson, S. E., Cohen, J. G., Sellgren, K., Mould, J., and Frogel, J. A. 1980, *Ap. J.*, **240**, 779.
Pierce, M. J. 1986, *A.J.*, **92**, 285.
Robin, A., and Crézé, M. 1986, *Astr. Ap.*, **157**, 71.
Rubin, V. C., and Ford, W. K. 1971, *Ap. J.*, **170**, 25.
Rubin, V. C., Ford, W. K., and Kumar, C. K. 1973, *Ap. J.*, **181**, 61.
Sandage, A. R., Becklin, E. E., and Neugebauer, G. 1969, *Ap. J.*, **157**, 55.
Sanders, R. H. 1981, *Ap. J.*, **244**, 820.
Scoville, N. Z., and Sanders, D. 1987, in *Interstellar Processes*, ed. D. Hollenbach and H. Thronson (Dordrecht: Reidel), p. 21.
Scoville, N. Z., Soifer, B. T., Neugebauer, G., Young, J. S., Matthews, K., and Yerka, J. 1985, *Ap. J.*, **289**, 129.
Scoville, N. Z., and Young, J. S. 1983, *Ap. J.*, **265**, 148.
Smith, J. 1982, *Ap. J.*, **261**, 463.
Soifer, B. T., Houck, J., and Neugebauer, G. 1987, *Ann. Rev. Astr. Ap.*, **25**, 187.
Telesco, C. M., Decher, R., and Gatley, I. 1986, *Ap. J.*, **302**, 632.
Telesco, C. M., and Gatley, I. 1984, *Ap. J.*, **284**, 557.
Telesco, C. M., and Harper, D. A. 1980, *Ap. J.*, **235**, 392.
Tenorio-Tagle, G., Bodenheimer, P., and Yorke, H. W. 1985, *Astr. Ap.*, **145**, 70.
Thronson, H. A., Hunter, D. A., Telesco, C. M., Greenhouse, M. A., and Harper, D. A. 1988, *Ap. J.*, submitted.
Thronson, H. A., Walker, C. E., Walker, C. W., and Maloney, P. 1987, *Ap. J.*, **318**, 645.
Thronson, H. A., and Telesco, C. M. 1986, *Ap. J.*, **311**, 98.
van den Bergh, S. 1987, in *Proc. ESO Workshop on SN 1987a*, in press.
Weedman, D. W. 1969, *Ap. J. (Letters)*, **155**, L129.
Weliachew, L., and Gottesmann, S. T. 1973, *Astr. Ap.*, **24**, 59.
Woltjer, L. 1959, *Ap. J.*, **130**, 38.
Wynn-Williams, C. G. 1982, *Ann. Rev. Astr. Ap.*, **20**, 587.
Zaritsky, D., and Lo, K. Y. 1986, *Ap. J.*, **303**, 66.

M. A. Greenhouse and H. A. Thronson: Department of Physics and Astronomy, Box 3905, University of Wyoming, Laramie, WY 82071