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A TRIGGERING MECHANISM FOR ENHANCED STAR FORMATION IN COLLIDING GALAXIES

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ABSTRACT

We propose a physical mechanism to explain the origin of the intense burst of massive-star formation seen in colliding/merging, gas-rich, field spiral galaxies. We explicitly take account of the different parameters for the two main mass components, H_2 and H I, of the interstellar medium within a galaxy and follow their consequent different evolution during a collision between two galaxies. We also note that, in a typical spiral galaxy—like our galaxy, the Giant Molecular Clouds (GMCs) are in a near-virial equilibrium and form the current sites of massive-star formation, but have a low star formation rate. We show that this star formation rate is increased following a collision between galaxies. During a typical collision between two field spiral galaxies, the H I clouds from the two galaxies undergo collisions at a relative velocity of ~ 300 km s^{-1}. However, the GMCs, with their smaller volume filling factor, do not collide. The collisions among the H I clouds from the two galaxies lead to the formation of a hot, ionized, high-pressure remnant gas. The overpressure due to this hot gas causes a radiative shock compression of the outer layers of a preexisting GMC in the overlapping wedge region. This makes these layers gravitationally unstable, thus triggering a burst of massive-star formation in the initially barely stable GMCs.

The resulting value of the typical IR luminosity from the young, massive stars from a pair of colliding galaxies is estimated to be $\sim 2 \times 10^{11}$ $L_{\odot}$, in agreement with the observed values. In our model, the massive-star formation occurs in situ in the overlapping regions of a pair of colliding galaxies. We can thus explain the origin of enhanced star formation over an extended, central area approximately several kiloparsecs in size, as seen in typical colliding galaxies, and also the origin of starbursts in extranuclear regions of disk overlap as seen in Arp 299 (NGC 3690/IC 694) and in Arp 244 (NGC 4038/39). Whether the IR emission from the central region or that from the surrounding extranuclear galactic disk dominates depends on the geometry and the epoch of the collision and on the initial radial gas distribution in the two galaxies. In general, the central starburst would be stronger than that in the disks, due to the higher preexisting gas densities in the central region. The burst of star formation is expected to last over a galactic gas disk crossing time $\sim 4 \times 10^7$ yr. We can also explain the simultaneous existence of nearly normal CO galaxy luminosities and shocked H_2 gas, as seen in colliding field galaxies.

This is a minimal model, in that the only necessary condition for it to work is that there should be a sufficient overlap between the spatial gas distributions of the colliding galaxy pair.

Subject headings: galaxies: interactions — galaxies: interstellar matter — infrared: galaxies — stars: formation

1. INTRODUCTION

It has now been established that an interaction between gas-rich spiral galaxies can lead to a burst of star formation, as seen from the high infrared luminosities from the interacting galaxies (e.g., Joseph et al. 1984a; Lonsdale, Persson, & Matthews 1984; Cutri & McAlary 1985; Young et al. 1986). The stellar radiation is absorbed by the dust clouds and reradiated as thermal emission in the far-infrared (e.g., Rieke & Low 1972; Thronson & Harper 1979). The star formation in the interacting galaxies is characterized by a high star formation rate and efficiency, an initial mass function biased toward massive stars, and the centralized location of the star-forming regions (Rieke et al. 1980; Gehrz, Sramek, & Weedman 1983).

Further, *colliding or merging* galaxies exhibit star formation that is qualitatively and quantitatively different from that in the weakly interacting galaxies. *In this paper, we concentrate on the early stages of a merger of a pair of galaxies.* First, the total infrared luminosity from the colliding galaxies is high, $\sim 10^{11}$–10^{12} $L_{\odot}$, as, for example, in Arp 220 and in NGC 6240 (Joseph & Wright 1985; Becklin 1987; Sanders et al. 1986). This is about two orders of magnitude greater than that for the weakly interacting galaxies, and hence the colliding galaxies have been called the "super-starburst" galaxies (Joseph & Wright 1985; Rieke et al. 1985) or the "ultraluminous" galaxies (Wright, Joseph, & Meikle 1984; Sanders et al. 1988). From a statistical study of interacting galaxies, Solomon & Sage (1988) have shown that the closest interacting/colliding pairs are the most luminous infrared emitters. Second, the burst of star formation in the colliding galaxies is seen to occur over a large spatially extended area, of diameter approximately several kiloparsecs around the galaxy center (e.g., Wright et al. 1984; Joseph & Wright 1985; Rieke et al. 1985; Wright et al. 1988). In fact, for some colliding pairs of galaxies, particularly when high-resolution data are available, the major infrared emission has been detected from extended regions of the extranuclear galactic disk or a number of hotspots rather than from the nuclear, that is, the central 1 kpc region (Schweizer 1983; Graham et al. 1987; Sargent et al. 1987; Carico et al. 1988; Stanford et al. 1990).

In the past, it has been suggested that an interaction between two galaxies leads to gas infall into the nuclear region within a galaxy following tidal perturbations of the cloud orbits and

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dissipational cloud collisions (e.g., Keel et al. 1985; Sanders et al. 1988), or the gas infall could be due to gas drag and dynamical friction experienced by the clouds (Norman & Scoville 1988). Noguchi & Ishibashi (1986) and Hernquist (1989) have given a detailed numerical treatment of the gas infall problem, and in that they have been successful. However, Hernquist has not specified a physical mechanism to convert this gas into stars. He has assumed an increase in the central gas density to be a sufficient criterion for the onset of starburst. Noguchi & Ishibashi (1986) and Sanders et al. (1988) assume that the higher central gas density, following gas infall, results in a higher rate of cloud collisions, which is claimed to yield an increase in the central star formation rate. However, if cloud-cloud collisions were in fact responsible for the burst of star formation, then one would expect to see a higher CO luminosity per unit cloud mass for the lower mass clouds. Such a correlation is not found to be valid at least for the Giant Molecular Clouds (hereafter, "GMCs"), in our galaxy (Mooney & Solomon 1988).

Thus, these earlier models, involving gas infall, do not specify a detailed physical mechanism for triggering starbursts in colliding galaxies. Also, these models do not yield quantitative estimates for the value of the very high infrared luminosity ($\sim 10^{11}$–10^{12} $L_\odot$) seen from colliding galaxies. Finally, these models describe the late stages of a merger, that is, several dynamical time scales after the first impact; whereas, we show that the evolution of a realistic, two-component interstellar medium, following a physical collision between two spiral galaxies, would first lead to a burst of star formation in situ in regions of overlap, before the gas infall can occur.

Harwit et al. (1987) have proposed that the infrared emission comes from a direct collision between molecular clouds in the two colliding galaxies. For their model to work, the collision between the galaxies has to be edge-on and hence would require too high a collision rate between galaxies, if it were to produce the observed percentage of infrared luminous galaxies. Also, the model by Harwit et al. cannot yield the observed high ratio of infrared luminosity to gas mass.

On the smaller spatial scale, the specific details of the star formation process, for example, the stellar initial mass function, have been modeled well by Rieke et al. (1980) and Gehrz et al. (1983). We incorporate their results while obtaining the values of IR luminosity from our model (§ 3).

In this paper, we *propose a physical model which explains the origin and the observed characteristic properties of bursts of massive-star formation, seen in pairs of colliding, gas-rich, field, spiral galaxies.* That is, we specifically concentrate on the case of super-starburst galaxies. Our model explicitly takes account of the two main mass components of the interstellar medium (hereafter, ISM) within a galaxy—the molecular hydrogen gas, H_2, and the atomic hydrogen gas, H I. The characteristic values for their parameters are taken to be identical to those observed in our galaxy. We also note that in our galaxy, the H_2 component is mainly distributed in the GMCs, and the GMCs constitute the sites of current star formation. The GMCs are gravitationally bound and in a near-virial equilibrium, with the pressure within a GMC, $P_{\mathrm{GMC}} \gg$ the initial ambient interstellar pressure acting on a GMC.

We show that the two ISM mass components, H_2 and H I, behave differently during a galaxy-galaxy collision. Due to the larger filling factor for H I, the H I clouds from the two galaxies undergo collisions while the GMCs do not, except in the rare case of an edge-on collision between the two galaxies. The collisions among the H I clouds lead to the formation of hot, ionized, high-pressure remnants which cause P_{ambient} around a GMC to be $\gg P_{\mathrm{GMC}}$. This overpressure around a preexisting GMC causes a radiative shock compression of the outer layers of a GMC, which triggers a burst of massive-star formation in these layers.

This is a minimal model, in that it only requires that there be a sufficient overlap between the gas distributions in the two galaxies in order to be able to explain the observed properties of a starburst in colliding galaxies. We obtain a quantitative estimate for the resulting high infrared luminosity and the high ratio of infrared luminosity to gas mass. We can also explain the spatially extended distribution of the starburst regions, including the starburst in regions of disk overlap as in Arp 299 (NGC 3690/IC 694) and in Arp 244 (NGC 4038/39); and also, the simultaneous existence of nearly normal CO galaxy luminosity and the shocked H_2 gas, as seen in colliding, field spiral galaxies. In addition, we can also explain the absence of super-starbursts in cluster galaxies.

In § 2 we discuss the details of the physical mechanism for triggering a starburst in colliding galaxies. Section 3 contains the results from this model and a comparison with observations, and § 4 contains a summary of the paper.

2. PHYSICAL MECHANISM FOR STARBURSTS IN COLLIDING GALAXIES

In this section, we consider the detailed evolution of a two-component (H_2 and H I) ISM leading to a burst of star formation, resulting from the collision of two spiral galaxies. This is clearly a dynamic process, and we present a simplified picture of the net effect on a GMC due to the collision between the two galaxies. For the sake of convenience, we assume that the ISM in each of the colliding galaxies is identical to that in our galaxy. First, consider the behavior of gas clouds in overlapping the galactic disks (§§ 2.1–2.3). Section 2.4 describes the evolution of ISM in the central 1 kpc region of overlap.

2.1 *Cloud Parameters*

The parameters characterizing each of the two main mass components of the ISM are R_c, the cloud radius; n, the number density of hydrogen atoms or molecules within a cloud (for the H I clouds and the GMCs, respectively); σ, the internal, three-dimensional velocity dispersion within a cloud; T_{eff}, the effective temperature within a cloud ($= \mu m_{\mathrm{H}} \sigma^2 / 3k_{\mathrm{B}}$), where k_{B} is the Boltzmann constant and μ is the mean molecular weight or the average atomic mass per free particle, in units of the amu, or m_{H} ($= 1.67 \times 10^{-24}$ g)—we assume a cosmic gas abundance, so that the fraction of helium is 10% by number of the hydrogen atoms; f, the *volume* filling factor; and z, the total vertical scale height (FWHM) of the distribution of the component. The corresponding quantities for the H_2 and H I components are denoted by the subscripts GMC and H I, respectively.

For the GMCs in the galactic disk, $(R_c)_{\mathrm{GMC}} = 25$ pc, $n_{\mathrm{GMC}} =$ the number density of hydrogen molecules $= 100$ cm^{-3}, $\sigma_{\mathrm{GMC}} = 4$ km s^{-1}, $\mu_{\mathrm{GMC}} = 2.8$—this is specified per hydrogen molecule, $(T_{\mathrm{eff}})_{\mathrm{GMC}} = 2 \times 10^3$ K, $f_{\mathrm{GMC}} = 0.01$, and $z_{\mathrm{GMC}} = 0.13$ kpc (Sanders, Solomon, & Scoville 1984; Sanders, Scoville, & Solomon 1985).

For the H I clouds in the galactic disk, $(R_c)_{\mathrm{H\,I}} = 5$ pc, $n_{\mathrm{H\,I}} =$ the number density of hydrogen atoms $= 20$ cm^{-3}, $\sigma_{\mathrm{H\,I}} = 1$ km s^{-1}, $\mu_{\mathrm{H\,I}} = 1.4$ (this is specified per hydrogen atom), $(T_{\mathrm{eff}})_{\mathrm{H\,I}} = 50$ K, $f_{\mathrm{H\,I}} = 0.1$, and $z_{\mathrm{H\,I}} = 0.2$ kpc (Spitzer 1978; Kulkarni & Heiles 1988, KH88 hereafter).

Thus we consider H I to be totally in the cold matter (CM) phase, initially ignoring the warm, neutral matter (WNM) phase (see KH88 for details of the various H I phases) because no data are available for the WNM in the inner Galaxy. Moreover as KH88 argue, the best model for the ISM in the inner Galaxy is the three-phase, supernova-dominated model of McKee & Ostriker (1977) and as per this model the amount of mass in the WNM phase is only 2% of the mass in the CM phase. Hence, in the region of interest, that is, in the inner Galaxy where the GMCs are located, one may consider H I to consist only of the CM phase.

It turns out that the analysis in this paper is most sensitive to the values for f, the volume filling factor, and z, the total gas scale height in the disk. Hence if our model works for the CM phase, it would also be valid for the other components of H I, which have higher filling factors. Later on, we shall comment on the higher resulting star formation rate if a WNM phase were to be included in the inner Galaxy, with the parameters as for the local WNM.

Note that even for the CM phase, the actual H I distribution may be more in the form of sheets or filaments with embedded higher density clumps or as envelopes around the GMCs (see KH88). Taking account of such spatial distributions would merely complicate the algebra without affecting the overall basic results from our model. Hence, for the sake of simplicity, we consider H I to be in the form of spherical clouds, with parameters as specified above.

2.2. *Evolution of ISM During a Galaxy-Galaxy Collision*

During a galaxy-galaxy collision, the clouds of a given ISM component will collide with those from the other galaxy, if their mean free path, λ, is less than δ, the size of the overlapping region. Spherical clouds of radii R_c, of an ISM component of a volume filling factor f, will have a mean free path $\lambda = (2/3)R_c/f$. For a face-on collision between galaxies, δ is a minimum $= z$.

The mean free path of a H I cloud $= 2/3[(R_c)_{\mathrm{H\,I}}/(f)_{\mathrm{H\,I}}] = 33$ pc is much smaller than $z_{\mathrm{H\,I}}$, hence the H I clouds from the two galaxies will undergo mutual collisions even in a direct face-on collision between the two galaxies.

A GMC, on the other hand, has a mean free path equal to $2/3[(R_c)_{\mathrm{GMC}}/(f)_{\mathrm{GMC}}] = 1.7$ kpc $> z_{\mathrm{GMC}} = 0.13$ kpc. Hence, the GMCs from the two galaxies will not undergo collisions, except in the rare case of an edge-on collision between galaxies.

Thus, the different values of the parameters for the two ISM components, especially the smaller volume filling factor for the GMCs, are responsible for their completely different evolution.

Now, the typical three-dimensional relative velocity, V_{rel}, for field or group galaxies is ~ 300 km s^{-1} (Holmberg 1940). Hence, during a collision between a pair of field galaxies, the H I clouds from the two galaxies collide with a relative velocity of ~ 300 km s^{-1}. Since this speed is much greater than the sound speed within an individual H I cloud ($= 0.7$ km s^{-1}; Spitzer 1978), the collision is characterized by a high Mach number (> 1), and it causes a strong shock wave to propagate at the interface of the two colliding H I clouds, and their kinetic energy of relative motion is thermalized. During the adiabatic phase, the velocity of this shock in the center of mass frame of the two clouds, in the limit of large Mach numbers, is equal to $(1/3)(V_{\mathrm{rel}}/2)$ Smith 1980. Hence, in the rest frame of a cloud, the shock velocity is equal to $(4/3)(V_{\mathrm{rel}}/2)$.

The values of the total particle number density, n_{rem}, and the temperature, T_{rem}, of the postshock remnant of a collision between two H I clouds are given as follows (e.g., Dyson & Williams 1980):

$$n_{\mathrm{rem}} = \frac{4\mu_{\mathrm{H\,I}} n_{\mathrm{H\,I}}}{\mu_{\mathrm{rem}}}\,, \tag{1}$$

$$T_{\mathrm{rem}} = \left(\frac{3}{16}\,\frac{\mu_{\mathrm{rem}} m_{\mathrm{H}}}{k_{\mathrm{B}}}\right)\left(\frac{2}{3}\,V_{\mathrm{rel}}\right)^2 = \left(\frac{\mu_{\mathrm{rem}} m_{\mathrm{H}}}{3k_{\mathrm{B}}}\right)\left(\frac{V_{\mathrm{rel}}}{2}\right)^2, \tag{2}$$

where $\mu_{\mathrm{rem}} = 0.61$ per free particle, for a fully ionized gas of cosmic abundance. For $V_{\mathrm{rel}} = 300$ km s^{-1}, we get $n_{\mathrm{rem}} = 184$ cm^{-3} and $T_{\mathrm{rem}} = 5.5 \times 10^5$ K.

Since the kinetic energy of relative motion between the two clouds is much greater than the internal binding energy of the individual H I clouds, the collision results in a remnant consisting of free, that is, gravitationally unbound, fully ionized gas with parameters as given above. The collision remnant remains within a galaxy and is not left at the center of mass of the system, because $(V_{\mathrm{rel}}/2)$ is smaller than the escape velocity velocity from an individual galaxy.

The hot gas in the remnants cools rapidly via radiative line emission. The cooling time, t_{cooling}, for hot, ionized gas is given by

$$t_{\mathrm{cooling}} = \tfrac{3}{2} k_{\mathrm{B}}\, T n_{\mathrm{rem}}/[(dE/dt)_{\mathrm{loss}}] = \frac{(3/2)k_{\mathrm{B}}\, T}{6.2 \times 10^{-19}\, T^{-0.6}(n_p 0.43)}\ \mathrm{s} \tag{3}$$

for 10^5 K $< T < 4 \times 10^7$ K (Raymond, Cox, & Smith 1976; McKee & Cowie 1977). The term in the square brackets is proportional to n_p^2, where n_p is the proton number density. We have set the ratio of n_p to n_{rem}, the total particle density, to be equal to 0.43, as appropriate for a fully ionized gas of cosmic abundance.

Therefore, for the gas in the collision remnants of H I clouds, $t_{\mathrm{cooling}} = 4.9 \times 10^2$ yr. This cooling time is $\ll$ the gas disk crossing time $\sim 4 \times 10^7$ yr (§ 3). Thus, the net effect on the H I component of a galaxy-galaxy collision is to distort the H I velocity field, and this is indeed observed to be the case for the ultraluminous galaxies (Mirabel & Sanders 1988).

Next, we consider the effect of the H I-cloud collision remnants on a GMC. On its formation, the pressure in a remnant is equal to $P_{\mathrm{rem}} = n_{\mathrm{rem}} k_{\mathrm{B}} T_{\mathrm{rem}} = 1.0 \times 10^8 k_{\mathrm{B}}$ K cm^{-3} which corresponds to an average ambient pressure, P_{ambient}, of $\sim 5.5 \times 10^5 k_{\mathrm{B}}$ K cm^{-3} (with $\langle n \rangle_{\mathrm{ISM}} \sim 1$ cm^{-3}; Spitzer 1978). This is greater than the pressure within a GMC, $P_{\mathrm{GMC}} = (100\ \mathrm{cm}^{-3}) k_{\mathrm{B}} (2 \times 10^3\ \mathrm{K}) = 2.0 \times 10^5 k_{\mathrm{B}}$ K cm^{-3}, where the GMC parameters are as defined in § 2.1. Note, however, that the very concept of an average ambient pressure due to the remnants is not meaningful in this case because the time scale for the collision between a GMC and a H I cloud is $\gg t_{\mathrm{cooling}}$ for the remnant gas. However, a GMC can still be affected by the higher pressure in the surrounding gas if the GMC is nearly uniformly surrounded by, and is in direct contact with, a few H I clouds to begin with, as is indeed the case when $f_{\mathrm{H\,I}} \gg f_{\mathrm{GMC}}$. Hence, we assume the effective ambient pressure around a GMC to be equal to $\sim P_{\mathrm{rem}}$. This assumption of a uniform overpressure would be better justified if the more realistic (sheetlike) distribution of H I with its larger volume and area filling factors were to be used.

Thus, during a collision between two spiral galaxies, the preexisting GMCs in the overlapping wedge experience a higher pressure from the surrounding hot gas. It then follows from simple thermodynamics that this overpressure compresses the outer shell of a GMC. Another possible effect of a GMC surrounded by hot gas is the evaporation of gas from the

GMC. Applying the results of McKee & Cowie (1977), one finds that the evaporation from a GMC can be neglected on time scales ~ the cooling time for the remnant gas.

Now, the compression of a GMC can occur only as long as the pressure in the remnants is greater than $P_{\rm GMC}$. The pressure in a remnant of a H I–H I cloud collision decreases with time, due to the cooling of the hot, ionized gas in the remnant. Hence, it may seem that the compression due to the overpressure can occur only over a cooling time. However, the effective overpressure time, $t_{\rm comp}$, during which a GMC will experience a higher external pressure and during which its outer layers may get compressed, is equal to the maximum of $t_{\rm cooling} = 4.9 \times 10^2$ yr and the H I cloud crossing time $= (R_c)_{\rm H\,I}/V_{\rm rel} = 1.7 \times 10^4$ yr. Hence,

$$t_{\rm comp} = (R_c)_{\rm H\,I}/V_{\rm rel} \; . \tag{4}$$

Now, the gas in the remnant expands at a speed equal to $C_{\rm rem}$, the sound speed in the remnant gas, defined as follows:

$$C^2_{\rm rem} \equiv \frac{k_{\rm B}\, T_{\rm rem}}{\mu_{\rm rem}\, m_{\rm H}} \; . \tag{5}$$

Using the expression for $T_{\rm rem}$ as in equation (2), this reduces to

$$C_{\rm rem} = \frac{V_{\rm rel}}{12^{1/2}} \; . \tag{6}$$

This causes a compression of a GMC shell at a velocity, V_s, defined as follows (e.g., Spitzer 1978):

$$V_s \equiv \left(\frac{\mu_{\rm rem}\, n_{\rm rem}}{\mu_{\rm GMC}\, n_{\rm GMC}}\right)^{1/2} C_{\rm rem} \; . \tag{7}$$

Substituting the expressions for $n_{\rm rem}$ and $C_{\rm rem}$ from equations (1) and (6), respectively, and using $\mu_{\rm H\,I} = 1.4$, and $\mu_{\rm GMC} = 2.8$, this simplifies to

$$\begin{aligned} V_s &= \left(\frac{1}{6}\,\frac{n_{\rm H\,I}}{n_{\rm GMC}}\right)^{1/2} V_{\rm rel} \\ &= 55 \text{ km s}^{-1} \left(\frac{n_{\rm H\,I}}{20 \text{ cm}^{-3}}\right)^{1/2} \left(\frac{n_{\rm GMC}}{100 \text{ cm}^{-3}}\right)^{-1/2} \left(\frac{V_{\rm rel}}{300 \text{ km s}^{-1}}\right) . \end{aligned} \tag{8}$$

Note that for the typical parameters used, $V_s = V_{\rm rel}/30^{1/2} = 55$ km s^{-1}. This is much greater than $C_{\rm GMC}$, the sound speed in a GMC, where $C_{\rm GMC} = (\sigma^2_{\rm GMC}/3)^{1/2} = 2.3$ km s^{-1}. Hence, during the compression, a shock is developed at the GMC boundary. This shock is driven at a speed V_s, with respect to the GMC rest frame, into the GMC for $t_{\rm comp} \sim 2 \times 10^4$ yr. A more rigorous calculation than that attempted here would include the resulting decrease in V_s with the decrease in the external pressure.

To begin with, the shock is adiabatic, and because of the high Mach number (= 55/2.3 = 24), the asymptotic values for the total particle number density and the temperature in the postshock region in a GMC shell are given respectively by (Dyson & Williams 1980):

$$n_{\rm shell} = \frac{4\mu_{\rm GMC}\, n_{\rm GMC}}{\mu_{\rm shell}} \tag{9}$$

$$T_{\rm shell} = \left(\frac{3}{16}\,\frac{\mu_{\rm shell}\, m_{\rm H}}{k_{\rm B}}\right) V_s^2 \; , \tag{10}$$

where $\mu_{\rm shell} = 0.61$ per free particle, for a fully ionized gas of cosmic abundance. For the typical values of the parameters used, these give $n_{\rm shell} = 1.8 \times 10^3$ cm^{-3}, and $T_{\rm shell} = 4 \times 10^4$ K. For these values of these parameters, the gas cooling time, $t_{\rm cooling}$, is ~2 yr (from eq. [3] with the cooling rate for $T_{\rm shell}$ as given by McKee & Cowie 1977). This is $\ll$ the dynamic time scale $= t_{\rm comp} = 1.7 \times 10^4$ yr. Hence, the shock can be taken to be radiative in the later stages, and the postshock gas density in the radiative phase in the outer shell of a GMC, $n_{\rm final}$, in the asymptotic limit is given by (Dyson & Williams 1980)

$$\frac{n_{\rm final}}{n_{\rm GMC}} = \frac{16}{3}\,\frac{T_{\rm shell}}{(T_{\rm eff})_{\rm GMC}} \; . \tag{11}$$

Hence, $n_{\rm final}$, the postshock density in the shocked gas in the outer shell of a GMC, is equal to 1.1×10^4 cm^{-3}.

We note that at these shock velocities greater than 50 km s^{-1}, the molecules are dissociated, however, they re-form fast—even before the gas has cooled to its initial temperature (Neufeld 1990). Hence, the expression for $n_{\rm final}$ as in equation (11) does denote the number density of hydrogen molecules in the post-shock region in the shell.

So far, we have discussed the evolution of the ISM during a collision between two field galaxies, with a $V_{\rm rel} \sim 300$ km s^{-1}. In contrast, for the dynamically complementary case of spiral galaxies in a cluster of galaxies, the typical $V_{\rm rel} \sim 2000$ km s^{-1} (e.g., Huchra 1985), which is gresater than twice the escape velocity from a typical spiral galaxy. Following a fast collision between two spirals in a cluster, the H I component would be left behind in the center of mass of the two galaxies. Thus, the H I gas would be removed from the galaxies (Spitzer & Baade 1951), while the GMCs and the stars with their lower filling factors would be unaffected by the collision (Valluri & Jog 1990). In this case, the starburst as outlined in the present paper will not occur. This prediction is borne out by observations, since there are no detected super-starburst galaxies in clusters of galaxies at the present epoch. Note that, at the present epoch, clusters of galaxies contain few blue galaxies, less a few per cent of the total (Kennicutt, Bothun, & Schommer 1984; Bothun & Dressler 1986; Mellier et al. 1988). Furthermore, these blue galaxies in nearby clusters have luminosities much lower than those observed for the super-starburst field galaxies (Kennicutt et al. 1984; Moss, Whittle, & Irwin 1988).
clusters of galaxies is much higher; (e.g., Butcher & Oemler 1984). We will address this question in the light of our model in a future paper (Jog 1991).

2.3. *Enhanced Star Formation In the Radiatively Shocked Gas*

Before the galaxy-galaxy collision, a GMC in the galactic disk is in a near virial equilibrium, that is, 2 KE + PE = 0, where KE and PE are respectively the kinetic energy and the gravitational potential energy of the GMC. That is, even before a GMC experiences a high $P_{\rm ambient}$, it is already on the brink of being unstable. Following the radiative shock compression of the outer shell of a GMC, the density in the postshock region in the shell is increased to 1.1×10^4 cm^{-3}, while the effective temperature remains constant. Hence, the KE remains unchanged while the PE becomes more negative, that is, the virial theorem is no longer satisfied by the shocked gas in the shell and it becomes gravitationally unstable as shown next.

In order to check whether the gas in the thin, shocked outer layers of a GMC is gravitationally unstable, the concept of

Jeans mass (as in the three-dimensional case) is not meaningful. Instead, in this case, $l_{\rm min}$, the minimum size of an unstable perturbation in the disk is given by a local, linear perturbation analysis for a thin disk supported by pressure (Toomre 1964): $l_{\rm min} = C^2_{\rm GMC}/G\Sigma$, where $C_{\rm GMC}$ is the sound speed in a GMC and Σ is the surface mass density of the disk. In our case, Σ is equal to the surface mass density of the shocked layer/shell, and is equal to $(n_{\rm GMC}\,\mu_{\rm GMC}\,m_{\rm H})(V_s\,t_{\rm comp})$. $l_{\rm min}$ is measured in a direction normal to the radial direction of compression. Note that this result was earlier shown to be valid, to within a factor of few, for a thin, shocked layer of gas (Ostriker & Cowie 1981), and for a thin, spherical, shocked layer of gas (Vishniac 1983)—both of these were obtained for pressure-bound gas in the context of explosive galaxy formation.

For the typical parameters in § 2.2, $l_{\rm min} \sim 200$ pc, which is in fact less than or equal to the spherical size of the shocked layer of a GMC. Thus, the gas in the thin, shocked, outer layer of a GMC is barely unstable to the growth of gravitational instabilities. Note that the above inequality, indicating the instability of the layer, holds better if somewhat higher (and more realistic) values of the H I filling factor, or $n_{\rm GMC}$ (~ 250 cm^{-3}), were to be used.

Further evolution of the gas leading to star formation clearly involves nonlinear evolution of the gas, which is beyond the scope of this paper. Note that the onset of star formation in the GMCs, which are bound by self-gravity, and have $P_{\rm GMC} \gg$ the initial ambient pressure in the galaxy, requires less stringent conditions than required for the onset of star formation in pressure-bound clouds (for the latter case see, e.g., Elmegreen & Elmegreen 1978). For example, the free-fall time in the GMC shell need not be less than the compression time ($= 1.7 \times 10^4$ yr) unlike in the pressure-bound clouds.

Now, the fraction of a GMC mass, say α_m, that consists of the shocked, high-density gas in the outer layers of a GMC, is given by:

$$\alpha_m \equiv \frac{4\pi[(R_c)_{\rm GMC} - \Delta R]^2 \Delta R}{(4/3)\pi[(R_c)_{\rm GMC}]^3}\,, \tag{12}$$

where

$$\Delta R \equiv V_s\,t_{\rm comp} = V_s (R_c)_{\rm H\,I}/V_{\rm rel}\,, \tag{13}$$

where V_s, the shock velocity, is defined by equation (8). Hence, equation (13) simplifies to the following:

$$\Delta R = \left(\frac{1}{6}\,\frac{n_{\rm H\,I}}{n_{\rm GMC}}\right)^{1/2} (R_c)_{\rm H\,I}\,. \tag{14}$$

We define

$$X \equiv \frac{\Delta R}{(R_c)_{\rm GMC}} = 0.037\left\{\left[\frac{n_{\rm H\,I}}{20\ {\rm cm}^{-3}}\right]^{1/2}\left[\frac{n_{\rm GMC}}{100\ {\rm cm}^{-3}}\right]^{-1/2} \times \left[\frac{(R_c)_{\rm H\,I}}{5\ {\rm pc}}\right]\left[\frac{(R_c)_{\rm GMC}}{25\ {\rm pc}}\right]^{-1}\right\}. \tag{15}$$

Hence,

$$\alpha_m = 3X(1 - X)^2\,. \tag{16}$$

For the typical values of the parameters as used above, $\alpha_m = 0.10$. Therefore, for a gas-rich, infrared ultraluminous galaxy, with a total molecular gas content, $M_{\rm gas} \sim 10^{10}\ M_\odot$ (Sanders et al. 1988; Solomon & Sage 1988), the total amount of shocked gas in the GMCs is $= \alpha_m \times 10^{10}\ M_\odot$.

Note that only $\sim 10\%$ of the gas in the GMCs in the overlapping wedge is shocked; a large fraction of this is converted into stars, leaving the rest ($\sim 90\%$ of the GMC mass) undisturbed. Now, as usual, the CO luminosity from a cloud is proportional to the (unshocked) molecular cloud mass, even for the optically thick case, as long as the clouds have similar density and temperature (see, e.g., Sanders et al. 1984). Thus, we can explain the nearly normal CO galaxy luminosities (Solomon & Sage 1988; Jackson et al. 1989), and the simultaneous observation of small amounts of shocked H_2 gas ($\leq 1\%$ of the molecular gas), (see Joseph, Wright, & Wade 1984b; Lester, Harvey, & Carr 1988), as observed from the colliding galaxies.

The idea of enhanced star formation due to overpressure around preexisting GMCs as developed here can be extended to the case of a collision between two irregular galaxies, say, the Large Magellanic Cloud and the Small Magellanic Cloud, or a collision between an irregular galaxy and a giant spiral galaxy. The overpressure/compression time is larger in this case, because of the lower metallicities and the lower ISM densities in the irregular galaxies. In this case, the galaxy collision leads to a burst of formation of "young globular (or populous) star clusters" (Jog 1991).

Now, the effective duration of star formation is the crossing time for the gas in the two colliding galaxies, and is given by $d_{\rm gas}/V_{\rm rel}$, where $d_{\rm gas} = 12$ kpc is the dimension of the region containing the H_2 component as in our galaxy (Sanders et al. 1984). The typical crossing time is $\sim 4 \times 10^7$ yr.

Next, consider SFE, the star formation efficiency, or the conversion efficiency. That is, let SFE denote the fraction of shocked gas that is converted into stars. There are several indications that SFE increases at higher gas densities. First, at high gas densities the star formation time is short, hence there is less time for the negative feedback from the ionizing radiation from the O-B-A stars. Thus, SFE could be as high as 0.2–0.5 for star formation time $\sim 10^6$ to 3×10^5 yr, as argued by Larson (1987). Second, the detailed models, for example, by Rieke et al. (1980), for the parameters in a starburst region, also indicate that the SFE is typically 0.5. Finally, there is observational evidence that the SFE in colliding galaxies is ~ 30 times that in isolated galaxies (Mooney & Solomon 1988). Therefore, we assume the SFE to be 0.5, corresponding to a 50% star formation efficiency. Therefore, SFR, the average star formation rate, during a collision between galaxies, is given by

$$\mathrm{SFR} \equiv 13\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}\left(\frac{\alpha_m}{0.10}\right)\left(\frac{M_{\rm gas}}{10^{10}\ M_\odot}\right)\left(\frac{\mathrm{SFE}}{0.5}\right) \times \left(\frac{d_{\rm gas}}{12\ {\rm kpc}}\right)^{-1}\left(\frac{V_{\rm rel}}{300\ {\rm km\ s}^{-1}}\right). \tag{17}$$

Hence, for the typical parameters as above, SFR = 13 $M_\odot$ yr^{-1}. A comparison of the resulting $L_{\rm IR}$ from this calculated SFR with the observed values will be made in § 3.

Note that the SFR as per equation (17) is a lower limit on the calculated SFR if the massive-star formation in the shocked gas in the GMC shell were to lead to an induced, say, by supernova shocks, or sequential star formation in the interior of the GMCs, as has been suggested (e.g., Elmegreen & Lada 1977) for the case of star formation in pressure-bound clouds. However, in this case, the infrared luminosity per unit gas mass would be expected to be higher for a higher mass cloud, which is not found to be true for the galactic GMCs (Mooney & Solomon 1988).

So far, we have assumed the H I component to be fully in the CM phase and have ignored the WNM phase (§ 2.1). If the WNM were to be included, with say an equal mass in the CM and the WNM phases as for the solar neighborhood (KH88), and in addition if the WNM were to be distributed around the CM clouds, then the effective cooling time and hence the SFR would increase. If, on the other hand, the WNM were to be distributed as intercloud gas, then the overall $P_{\rm ambient}$ around a GMC in the overlapping wedge would be more uniform.

In our galaxy, at least some of the star-forming molecular clouds are observed to be surrounded by approximately equally massive, large H I envelopes (Deiter 1960; Gordon 1971; KH88). It is not known if all GMCs have such massive, extended H I envelopes. The actual SFR in this case would depend on the extent of the envelopes, the fraction of H I mass in the envelopes, and the filling factor for the H I gas.

It is interesting to calculate L_x, the net X-ray luminosity resulting from the line cooling of the remnants of the H I cloud collisions, which can be given as the thermal kinetic energy of the remnants radiated over the galactic gas disk crossing time, as follows:

$$L_x = 5 \times 10^{41}\ \mathrm{ergs}^{-1}\left(\frac{M_{\rm H\,I}}{3 \times 10^9\ M_\odot}\right)\left(\frac{T_{\rm rem}}{5.5 \times 10^5\ \mathrm{K}}\right) \times \left(\frac{d_{\rm gas}}{12\ \mathrm{kpc}}\right)^{-1}\left(\frac{V_{\rm rel}}{300\ \mathrm{km\ s^{-1}}}\right), \quad (18)$$

where we have assumed the total H I content of a galaxy within 6 kpc to be about one-third that of the H_2 content, as in our galaxy (e.g., Sanders et al. 1984). Thus, the typical EUV/soft X-ray luminosity, at ≤ 0.1 kev, from a pair of colliding field galaxies is calculated to be $\sim 5 \times 10^{41}$ ergs s^{-1}.

Normal galaxies are observed to have X-ray luminosities in the range of 10^{38}–10^{41} ergs s^{-1}, whereas the starburst galaxies tend to have enhanced X-ray emission greater than 10^{42} ergs s^{-1}, and the emission in the latter comes from spatially extended regions (Fabbiano 1989, and references therein). In physically colliding galaxies, as in Arp 244 (Fabbiano, Feigelson, & Zamorani 1982), and in Arp 220 (Eales & Arnaud 1988), a softer X-ray component of gaseous origin has been identified, in addition to the hard X-ray emission from the massive X-ray binaries and the young supernova remnants (Fabbiano 1989). Thus, our calculated value of soft X-ray luminosity may explain a part of the observed X-ray luminosity of gaseous origin from colliding galaxies.

2.4. *Evolution of ISM in the Central 1 kpc Region*

The discussion in §§ 2.1–2.3, including the equations for α_m, the fraction of shocked gas, and the SFR, was applicable for gas in the extranuclear disks of colliding galaxies. However, the overall picture for starbursts as outlined above would be equally applicable to the nuclear regions of the galaxies if the appropriate values for the gas parameters were to be used.

The average density within a molecular cloud in the central 1 kpc region of a typical spiral galaxy may be taken to be $\sim 3 \times 10^3$ cm^{-3} as deduced from the widespread detection of CS emission, the cloud size remains the same at $\sim$25 pc, and the average effective internal velocity dispersion is 12 km s^{-1}, corresponding to an observed line width (FWHM) of $\sim$30 km s^{-1} as in the central 1 kpc of our galaxy (Bally et al. 1987, 1988). Hence the effective internal temperature within these clouds is $\sim 2 \times 10^4$ K $[= \mu_{\rm GMC} m_{\rm H}\ (12\ \mathrm{km\ s^{-1}})^2/3k_{\rm B}]$. The internal pressure within a galactic-center GMC is therefore equal to $7 \times 10^7 k_{\rm B}$ K cm^{-3}.

The intercloud material is mostly molecular with $n_{\rm GMC} \sim$ 30–100 cm^{-3}, with an average $n_{\rm GMC} = 50$ cm^{-3} for the central 1 kpc region, and with a volume filling factor $\sim$1 (Bally et al. 1988). This follows from the strong CO emission seen over the entire central region of our galaxy, and the absence of significant H I emission. That is, the molecular clouds within the central region are uniformly surrounded by the low-density intercloud (molecular) material.

Now, following a collision between the disk of a glaxy and the central 1 kpc region of the other colliding galaxy, the average particle number density and the temperature in the intercloud remnants in the central 1 kpc are given respectively as $4\mu_{\rm GMC}\ (50\ \mathrm{cm^{-3}}/0.61) = 9 \times 10^2$ cm^{-3} and 5.5×10^6 K, respectively (see eq. [2]). Therefore, the average intercloud pressure is $5 \times 10^8 k_{\rm B}$ K cm^{-3}, which is greater than the internal cloud pressure $= 7 \times 10^7 k_{\rm B}$ K cm^{-3}. Hence, even in the central region, the H I-cloud collision-remnants can compress the preexisting molecular clouds, and a burst of massive-star formation would result, as outlined in §§ 2.2–2.3. In this case, the compression time would be larger due to the extensive uniform intercloud material surrounding a cloud. The value of α_m, the fraction of shocked gas, depends critically on the actual geometry of collision and could be larger than 0.1 in a large fraction of the cases. With $d_{\rm gas} = 1$ kpc, and the $M_{\rm gas}$ within this region being equal to $\sim 10^9\ M_\odot$, the resulting SFR and the $L_{\rm IR}$ would be larger than in the case of disk-disk collision considered in §§ 2.1–2.3. Thus, the central starburst, resulting from a direct physical collision between two galaxies, would in general be more luminous than the disk case, because of the higher preexisting ISM densities in the central region.

Section 3.2 contains a discussion of the spatial and temporal sequence of star-forming regions in colliding galaxies.

3. RESULTS

In this section, we present the results from our model and compare these with observational data. The results to be discussed are the star formation rate for the massive stars and the associated resulting infrared luminosity from the heated dust (§ 3.1), the spatial and temporal distribution of star-forming regions (§ 3.2), and the luminosity-to-mass ratio and the infrared-to-blue luminosity ratio (§ 3.3), for the regions undergoing a burst of star formation in a pair of colliding galaxies.

3.1. *The Massive-Star Formation Rate and the Resulting $L_{\rm IR}$.*

The stars formed in regions of high gas density are expected to be massive, greater than a few $M_\odot$ each. First, in regions of high gas density and of high star formation rate, there is a good coupling between gas and dust which increases the temperature, thus resulting in a higher critical/minimum value for the mass of a star formed (Larson 1986). Further, Rieke et al. (1980) and Gehrz et al. (1983) have shown that the best fit to a variety of observational data in the star-forming regions in colliding galaxies can be obtained when the typical mass of a star formed is taken to be $\sim$ a few $M_\odot$, with the minimum mass being greater than 3 $M_\odot$. That is, most of the stars formed are O-, B- and A-type stars. Hence, we assume that most of the stars formed in the shocked layers of GMCs are massive stars.

The total luminosity, $L_{\rm total}$, from the O-B-A stars, that is, stars with masses $\sim$ a few $M_\odot$ each, can be written as follows

(Scoville & Young 1983):

$$L_{\rm total} = \left[1.3 \times 10^{10}\left(\frac{L_\odot\ {\rm yr}}{M_\odot}\right)\right][{\rm SFR}\ (M_\odot\ {\rm yr}^{-1})]\ . \quad (19)$$

The first set of square brackets in equation (19) contains the total energy output over its lifetime per unit mass from a star of mass ~ a few $M_\odot$. This simple relation follows because most of the energy output from such a star occurs during the CNO cycle while it is on the main sequence.

For the typical calculated SFR of 13 $M_\odot$ yr^{-1} (eq. [17]), and assuming the stars formed to be of a few $M_\odot$ each, the resulting total infrared luminosity is given by equation (19) to be 2×10^{11} $L_\odot$, in agreement with typical observed values of $L_{\rm IR}$ (Joseph & Wright 1985; Becklin 1987; Sanders et al. 1986). While comparing these quantities, we have implicitly assumed that the major part of $L_{\rm total}$ would be reradiated thermally in infrared §§ 1, 3.3). Also note that even though the SFR (eq. [17]) is only a few times larger than that in our galaxy, the resulting $L_{\rm IR}$ is high in colliding galaxies due to the preferential formation of massive stars.

Note, however, that the calculated SFR is only accurate to within an order of magnitude of the above typical value, since it depends on a number of parameters, each of which could be uncertain to a factor of a few. Also, different spatial distributions of H I are possible as discussed in § 2.3, and these would affect the SFR. For example, an atomic component with a higher filling factor than assumed here would tend to give a larger value of SFR.

It is interesting to estimate the maximum calculated SFR and the corresponding $L_{\rm IR}$ in colliding galaxies. $M_{\rm gas}$ and $d_{\rm gas}$ can each vary at the most by a factor of a few compared to their respective values used in § 2.3. The star formation efficiency, SFE, can at the most be equal to 1. Also, the fraction of shocked gas, α_m can have a maximum value of 1. Therefore, the maximum calculated value of SFR can at the most be ~50 times the typical value obtained earlier from equation (17), and therefore the maximum calculated $L_{\rm IR}$ is predicted to be less than 10^{13} $L_\odot$, which is in agreement with the observed upper limit on $L_{\rm IR}$ from a pair of colliding galaxies. This upper limit on $L_{\rm IR}$ is a strong limit.

Thus, our model can provide a quantitative estimate of the SFR and explain the origin and the magnitude of the typical and the maximum observed values of $L_{\rm IR}$ in pairs of colliding field galaxies.

3.2. *Spatial and Temporal Distribution of Star-Forming Regions*

The overall scenario for the spatial and temporal distribution of the regions undergoing bursts of star formation in a pair of colliding galaxies would be as follows. A physical collision between two gas-rich, spiral galaxies, with a two-component ISM (H_2 and H I), first triggers a burst of massive-star formation in the overlapping/interpenetrating regions of the galaxies (§ 2). Recall that, for our model to yield the burst of star formation, the gas distributions in the colliding galaxies should overlap. The regions that overlap first may be the central 1 kpc/nuclear regions or could be the extranuclear disk regions of several kpc diameter, depending on the geometry of the collision and the initial radial distribution of gas in the colliding galaxies.

If the galactic disks collide first, as would be the most likely case since the cross section is largest for this case of an off-center collision, the collision would trigger a burst of star formation in the overlapping disk regions. Later on, depending on the geometry of collision, the disk region of one galaxy may collide with the central (~1 kpc) region of the other galaxy. This would trigger a stronger burst in the colliding central 1 kpc region. The net burst of star formation would last over a disk crossing time ~4×10^7 yr. This estimate is in an agreement with the duration of starburst as deduced from the modeling by Rieke et al. (1985) of the observational data for Arp 220 and NGC 6240. So far we have only considered in situ star formation in colliding galaxies.

As a result of the tidal interaction between the galaxies, the orbits of the gas clouds (and stars) in each galaxy are perturbed, leading to an increased rate of cloud-cloud collisions within each galaxy, $\leq 10^8$ yr *after* the perigalactic passage (e.g., Noguchi & Ishibashi 1986). There would be a net infall toward the nuclear region following these dissipational collisions (e.g., Sanders et al. 1988; Hernquist 1989), or due to the drag experienced by the gas clouds (Norman & Scoville 1988). Even in the extreme case, when the initial overlap is limited to the disk regions, the above process would lead to gas inflow of the GMC mass that is unaffected by the starburst in the overlap region, as well as the H I clouds—into the nuclear regions—where a second, stronger starburst could occur, the details of this case will be presented in a future paper.

The relative strength of $L_{\rm IR}$ from the central 1 kpc region and that from the surrounding extranuclear galactic disk region would, thus, depend on the physical parameters and the spatial distribution of gas (H_2 and H I) in the two galaxies as well as on the geometry and the epoch of collision.

Thus, our model can provide a natural explanation for the remarkable and heretofore puzzling observation of three starburst regions in the interacting system Arp 299 (NGC 3690/IC 694), two of which are located at the nuclei of the two galaxies (Gehrz et al., 1983; Telesco, Decher, & Gatley 1985) and the third, extranuclear disk region lies in the region of overlap or the "interaction zone" (Combes 1988; Nakagawa et al. 1989). Similarly, we can explain the two nuclear and one extranuclear regions of starbursts seen in the pair of colliding galaxies Arp 244 (NGC 4038/39) (Stanford et al. 1990). Interestingly, the main infrared emission in Arp 244 comes from the extranuclear region of overlap between the two galaxies.

Future infrared observations from space-borne instruments as well as the ground-based observations in the near-infrared will be able to provide a higher resolution information on $L_{\rm IR}$ in colliding galaxies and on whether the inner galactic disk or the nuclear infrared emission is the stronger in a particular pair of colliding galaxies.

A very late stage in the evolution of a merger of galaxies can be described as follows. After several dynamical time scales, the star formation would be concentrated in the central regions. The massive stars formed in the central regions of colliding galaxies would eventually die, that is, evolve to be degenerate objects such as the neutron stars, which may well coalesce to form a black hole or feed a preexisting black hole, thus powering an Active Galactic Nucleus (AGN) at the galaxy center (Weedman 1983; Norman & Scoville 1988). Therefore, it is not surprising that a large fraction of colliding galaxies with strong $L_{\rm IR}$ ($> 10^{12}$ $L_\odot$) also exhibit an AGN spectrum (Becklin 1987; Sanders et al. 1988). A substantial contribution to $L_{\rm IR}$ in such cases may come from dust heated by the central AGN as in NGC 1068 (Telesco 1988).

3.3. $L_{\rm IR}/M_{\rm gas}$ *and* $L_{\rm IR}/L_B$ *from Colliding Galaxies*

The typical observed value of $L_{\rm IR}/M_{\rm gas}$ for the gas in the strongly interacting galaxies is in the range of ~10–25 $L_\odot$

$M_\odot^{-1}$ (Sanders et al. 1986). Most of this emission is powered by stars of $\sim$ a few $M_\odot$ each (§ 3.1), for which $L/M \sim 10^2$–10^3 $L_\odot$ $M_\odot^{-1}$ (Mihalas & Binney 1981). If the entire shocked gas in the GMC shells (with a mass $= \alpha_m M_{\rm gas} = 0.1 \times 10^{10}\ M_\odot$) were to form massive stars with, say, 50% efficiency, the the resulting $L_{\rm IR}$ would be $\sim 10^{11}$–10^{12} $L_\odot$, which overlaps with the observed range of $L_{\rm IR}$ in colliding galaxies (§ 1). The resulting value of $L_{\rm IR}/M_{\rm gas}$ would be $\sim$10–100 $L_\odot$ $M_\odot^{-1}$. Note that this estimate compares well with the value for $L_{\rm IR}/M_{\rm gas} \sim 20$ $L_\odot$ $M_\odot^{-1}$, as obtained from the detailed calculation of SFR and $L_{\rm IR}$ as in §§ 2.3 and 3.1.

For isolated or weakly interacting galaxies, the ratio of infrared luminosity to gas mass has a much smaller value $\sim$7, which interestingly is less than twice the value seen for the most active star-forming GMCs in our galaxy (Mooney & Solomon 1988). It has been suggested that the massive star formation in the galactic GMCs and in the weakly interacting galaxies is due to the cloud-cloud collisions for clouds within a galaxy (see Scoville, Sanders, & Clemens (1986), and Sanders et al. (1988), respectively). Note that in both these cases, the relative velocity between the clouds would be $\ll V_{\rm rel}$, and hence the shocks would be much weaker than in the case of colliding galaxies, and may thus result in the lower observed $L_{\rm IR}$.

Next, consider the ratio of infrared-to-blue luminosities, $L_{\rm IR}/L_B = L(80\ \mu{\rm m})/L(4400\ {\rm Å})$, from colliding galaxies. The quantity $L_{\rm IR}/L_B$ (often called the infrared excess) may be taken to be a measure of the ratio of the obscured, young stars to the old, average stellar population. Thus it is a measure of the starburst phenomenon.

The observed range of values of the infrared-to-blue luminosity ratio for the interacting/merging galaxies is large, from $\sim$0.5–50, but a very small fraction of these have a high infrared-to-blue luminosity ratio, say greater than 10 (Soifer et al. 1984; Lonsdale et al. 1984; Young et al. 1989). From these data, we find that *the galaxies undergoing a disk-disk collision, such as, Arp 244 (NGC 4038/9), have a low* $L_{\rm IR}/L_B$ in the above range. For Arp 244, this ratio is 1.41 (for 1–500 μm range; Young et al. 1989) or 0.08 (for the 80 μm band, Lonsdale et al. 1984). Arp 242 (NGC 4676), with a similar morphology, also has a small infrared-to-blue luminosity ratio of less than 1.8 (Lonsdale et al. 1984).

We note that a central starburst, or a highly evolved merger, on the other hand, is observed to be characterized by high values of $L_{\rm IR}/L_B \gg 1$ (also see Lonsdale et al. 1984). Some examples of evolved mergers ($\geq 10^9$ yr old) are Arp 220, Arp 243 (NGC 2623), and Arp 193 (IC 883). In each case, the morphology clearly shows a merged system of two disk galaxies, and the tidal tails. Further, the elliptical-like light profile is well-fitted by the $r^{1/4}$–de Vaucouleurs law, indicating that it represents a late stage in the evolution of a merger (Wright et al. 1990; Stanford & Bushouse 1991). These mergers have high $L_{\rm IR}/L_B$ values = 60.78, 13.34, and 13.03, respectively (Young et al. 1989).

We next explain this variation in the infrared-to-blue luminosity ratio in the light of our model. For the typical parameters used in this paper to study a disk-disk collision (§§ 2.1–2.3), the thickness of a GMC shell which is shock compressed is equal to $\sim$1 pc. With the molecular hydrogen density in a GMC, $n_{\rm GMC}$, of 100 cm^{-3}, the column density of hydrogen in this shell is 6×10^{20} cm^{-2}; this corresponds to an extinction A_V(mag) in the visual of 0.3 (Spitzer 1978). Further, the selective extinction $E(B-V) = A_B - A_V = A_V/3$. Hence, for the outer shocked shell in a GMC, $A_B = (4/3)A_V = 0.4$.

Now, assuming that the radiation absorbed in blue is reradiated thermally in the infrared by the dust, it can be shown from radiative transfer that the ratio of observed infrared to blue luminosities is equal to (e.g., Burbidge & Stein 1970)

$$\exp^{-\tau_B} = 1/[1 + L_{\rm IR}({\rm obs})/L_B({\rm obs})]\ , \tag{20}$$

where $\tau_B = A_B \times 0.92$. Thus, $L_{\rm IR}/L_B = 0.45$ for $A_B = 0.4$ This ratio is very sensitive to the value of τ_B. For example, if we were to consider a somewhat higher but reasonable molecular number density of a GMC = 250 cm^{-3}, then we would get a higher $\tau_B = 0.92$, and hence a higher $L_{\rm IR}/L_B = 1.51$. This result agrees reasonably well with the observed values for Arp 244 and Arp 242 given above.

Now, if one were instead to consider a collision between a galaxy disk and the central 1 kpc of another galaxy (see § 2.4), this ratio is higher. This is because, the clouds in the central region are denser, and also, the compression time is larger than that for the disk-disk case since the intercloud medium has filling factor of nearly 1 (§ 2.4). Hence A_V within a cloud would be much greater than 1, thus resulting in high values of infrared to blue luminosities as is indeed observed for the central starbursts. Note that for $A_V \geq 0.5$, a more accurate way to estimate dust extinction may involve taking account of the actual spatial distributions of gas and dust (Thronson et al. 1990).

For times $\gg$ the dynamic times, there would be further central concentration of gas due to gas infall (§ 3.2), thus resulting in even higher $L_{\rm IR}/L_B$—as in fact seen for the more evolved ($> 10^9$ yr), central starbursts in merging galaxies as in Arp 220. In such cases of very high central gas densities, there may even be sufficient cloud blocking so that the surface of one cloud is not visible due to blocking by another. Hence, for these extreme cases of high $L_{\rm IR}/L_B$ (> 10, say), a large fraction of the extinction may be due to this cloud blocking. Further, an important fraction of $L_{\rm IR}$ from dusty, disturbed, gas-rich systems (e.g., NGC 6240) may be contributed by the dust heated by the older stellar populations (Thronson et al. 1990). Finally, it should also be noted that for these very bright infrared sources, a substantial fraction of the infrared luminosity could be due to dust heated by the underlying AGN, as in NGC 1068 (Telesco 1988).

4. SUMMARY

To summarize, we have presented a simple physical mechanism for the origin of a burst of formation of massive stars in colliding, field spiral galaxies. We explicitly take into account the different parameters and the consequent different evolution of the H I clouds and the GMCs during a collision between a galaxy pair. We also note that in a normal galaxy like our galaxy, the GMCs are in a near-virial equilibrium and form the sites of current massive-star formation, but the star formation rate is low. We show that this star formation rate is increased following a collision between two galaxies. The collisions among the H I clouds from the two galaxies lead to the formation of a hot, ionized, high-pressure remnant gas that compresses the outer layers of preexisting GMCs. This causes the GMC shells to become gravitationally unstable, which triggers a burst of massive-star formation in the initially stable GMCs. In our model, the burst of massive-star formation occurs in situ in the overlapping regions of the colliding galaxies. The only necessary condition for this model to work is that there should be a sufficient overlap between the gas distributions of the colliding galaxies.

The model presented in this paper can explain in a cohesive way the following detailed, observed characteristics of the enhanced star-forming regions in colliding, field, spiral galaxies:

1.—We give a quantitative estimate for the resulting high L_{IR}, arising mostly due to the young, massive (O-B-A) stars, to be $\sim 2 \times 10^{11}$ $L_\odot$, in agreement with observational data.

2.—In our model, the enhanced star formation occurs in situ in the region of overlap/interpenetration between the two galaxies. Thus, we can explain the large observed central, spatial extent ~ several kpc size, of the starburst region, and also the origin of the starburst in the region of disk overlap, as in Arp 299 (NGC 3690/IC 694) (Nakagawa et al. 1989), and in Arp 244 (NGC 4038/39) (Stanford et al. 1990). The relative strength of the nuclear and the extranuclear infrared emission depends on the collision geometry and the epoch of collision, and on the initial radial distribution of gas in the two galaxies. The starburst in the central region is generally stronger due to the higher preexisting central ISM densities. We expect a typical burst of star formation to last for the galactic gas disk crossing time $\sim 4 \times 10^7$ yr.

3. We can explain the observed values of $L_{IR}/M_{gas} = 10$–25 $L_\odot$ $M_\odot^{-1}$ (Sanders et al. 1986) if the ~10% of the GMC mass that is shocked during the galaxy collision can form massive stars, of a few $M_\odot$ each, with an ~50% efficiency (§ 3.3).

4.—We can explain the nearly normal observed values of the CO luminosities for colliding galaxies (Solomon & Sage 1988), as arising from the large fraction (~90% in this model) of the GMC mass that is undisturbed by the collision. We can also explain the observed simultaneous existence in colliding galaxies of shocked H_2 (≤ 1% of molecular gas) as arising via the compression of the outer layers of a GMC by the remnants of the H I–H I cloud collisions.

5.—The EUV/soft X-ray luminosity, at ≤ 0.1 keV, resulting from the radiative cooling of the hot remnants of atomic cloud collisions from a pair of colliding galaxies is calculated to be $\sim 5 \times 10^{41}$ ergs s^{-1}. This could explain a part of the observed, soft X-ray luminosity of gaseous origin from the colliding, that is, super-starburst, galaxies (Fabbiano 1989).

6.—For the complementary case of a fast collision between two spiral galaxies in a cluster of galaxies, with V_{rel} greater than twice the escape velocity from a spiral galaxy; the net effect of the collision is the preferential removal of H I gas from the colliding galaxies while the components with lower filling factors, namely the H_2 gas and the stars, are left unaffected (Valluri & Jog 1990). Therefore, one would not expect the starburst scenario outlined in this paper to work for the cluster galaxies. This prediction is in agreement with the observation that there are no detected super-starburst or ultraluminous galaxies in clusters of galaxies at the present epoch.

7.—The idea of enhanced star formation due to overpressure around preexisting GMCs as developed in this paper can be extended to the case of a collision between two irregular galaxies, say the Large Magellanic Cloud and the Small Magellanic Cloud, or a collision between an irregular galaxy and a giant spiral galaxy. The compression time is larger in this case, due to the lower metallicities and the overall lower ISM densities in irregular galaxies. In this case, the galaxy collision leads to the formation of "young globular (or populous) star clusters" (see Jog 1991).

We expect the process for starburst outlined in the present paper to have been extremely effective at early epochs of the universe when the space density of galaxies was higher and hence galaxy-galaxy collisions were more frequent than at the present epoch. Also, the galaxies were presumably more gas rich at earlier epochs than at present. Thus, star formation in colliding galaxies would be important for studying the cosmological evolution of galaxies.

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