STARBURST-DRIVEN STARBURSTS IN THE HEART OF ULTRALUMINOUS INFRARED GALAXIES

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ABSTRACT

There is increasing evidence for the presence of blue super-star clusters in the central regions of ultraluminous infrared galaxies like Arp 220. Ultraluminous galaxies are thought to be triggered by galaxy mergers, and it has often been argued that these super-star clusters may form during violent collisions between gas clouds in the final phase of the mergers. We now investigate another set of models that differ from previous ones in that the formation of the super-star clusters is linked directly to the very intense starburst occurring at the very center of the galaxy. First, we show that a scenario in which the super-star clusters form in material compressed by shock waves originating from the central starburst is implausible because the objects so produced are much smaller than the observed star clusters in Arp 220. We then investigate a scenario (based on the Shlosman-Noguchi model) in which the infalling dense gas disk is unstable gravitationally and collapses to form massive gaseous clumps. Since these clumps are exposed to the external high pressure that is driven by the superwind (a blast wave that is driven by the collective effect of a large number of supernovae in the very core of the galaxy), they can collapse and then massive star formation may be induced in them. The objects produced in this kind of collapse have properties consistent with those of the observed super-star clusters in the center of Arp 220.

Subject headings: galaxies: individual (Arp 220) — galaxies: starburst — stars: formation

1. INTRODUCTION

Galaxy mergers provide a mechanism for the metamorphosis of galaxies, and sometimes they trigger intense star formation events (starbursts) in the central regions of the merger remnants (Toomre 1977; Schweizer 1982). When such intense starbursts happen, ultraluminous infrared galaxies (ULIGs) result because of the enormous energy released from the central regions of the galaxies (Soifer et al. 1984; Wright, Joseph, & Meikle 1984; Sanders et al. 1988; Sanders & Mirabel 1996). One of the remarkable properties found in such galaxy mergers is that a number of blue super-star clusters (SSCs) reside in their central regions (Lutz 1991; Ashman & Zepf 1992; Holtzman et al. 1992; Shaya et al. 1994; see for a review Zepf & Ashman 1993). One plausible idea is that such SSCs may be formed by violent collisions among gas clouds in the final phase of the galaxy mergers (Ashman & Zepf 1992; Zepf & Ashman 1993).

The SSCs in the mergers are then distributed over the circumnuclear regions that are spatially close to the currently active starburst core (cf. Lutz 1991; Shaya et al. 1994). Such SSCs, while common in the cores of ULIGs, are rarely seen in galaxies where there is no evidence for an intense burst of star formation at the very center. Therefore, it is intriguing to investigate physical relationships between the circumnuclear SSCs and the nuclear starburst and to address the following question: Is the formation of SSCs attributed to some effects of the nuclear starburst? This is the subject of the present Letter. The link between the concentrated starburst in the core and the formation of the SSCs is a fundamental difference between the models we discuss and those that rely on the violent collisions mentioned in the previous paragraph.

The nearest and best-studied ULIG is Arp 220 (z = 0.02), and we use it as a basis for comparison in the present work. In this galaxy, two nuclei exist with a projected separation of 350 pc (see, e.g., Condon et al. 1991). Recent optical and near-infrared imaging made with the Hubble Space Telescope (HST) has shown that about a dozen of the star-forming clumps are distributed in the circumnuclear region with a radius of several hundred parsecs in Arp 220 (Shaya et al. 1994; Scoville et al. 1998). In particular, the western nucleus of Arp 220 is surrounded by several clumps that are distributed along the north-south direction. In Figure 1, we show a schematic illustration of the spatial distribution of SSCs in Arp 220. These clusters are distributed within a radius of 700 pc from this western nucleus. The masses of SSCs are estimated to be \( \sim 10^6 - 10^8 \, M_\odot \), although these numbers depend on the assumed stellar populations (Shaya et al. 1994).

These SSCs are more massive and larger (\( \sim 10 \) pc) than typical globular clusters in the Galaxy. Nevertheless, it is possible that the formation of SSCs provides important information on the formation of globular clusters. Recent theoretical studies have suggested that globular clusters are envisaged as forming in giant molecular clouds, in the same way as we see star cluster formation in our Galactic disk (Harris & Pudritz 1994; McLoughlin & Pudritz 1996; Elmegreen & Efremov 1997). Early in the formation of the Milky Way, which is when the globular cluster formed, there may also have been considerable concentrated star formation, as the bulge and the central part of the disk formed. This hypothetical comparison provides a secondary motivation for investigating the possible role of these concentrated starbursts in galaxy cores in the formation of massive star clusters.

2. STARBURST-DRIVEN STARBURSTS IN ARP 220

Arp 220 shows a double-bubble structure with an extent of 13 kpc (Heckman, Armus, & Miley 1987; Heckman et al. 1996; see Fig. 1). Such a morphology is evidence for a superwind, i.e., a blast wave that is driven by a large number of supernovae (Tomisaka & Ikeuchi 1988; Heckman, Armus, & Miley 1990; Suchkov et al. 1994). A typical galactic-scale nuclear starburst forms numerous (\( > 10^5 \) ) massive stars during a short period (\( \sim 10^7 \) yr; Weedman et al. 1981; Balzano 1983).
can collimate the superwind along the direction perpendicular to the disk (Tomisaka & Ikeuchi 1988); such a disk is observed in Arp 220 by Scoville, Yun, & Bryant (1997). Gas in the inner parts of this dense, collimating disk will be affected by both the dynamical (e.g., shocks) and thermal (e.g., compression by the high-pressure hot gas) effects of the superwind, and it is these processes that we consider in the rest of this Letter. The physical processes we describe here are quite distinct from what might be happening in the outer regions of the galaxy, where the superwind interacts with the ambient hot diffuse coronal gas. At this stage, we note that in Figure 1, the SSCs are distributed along the direction almost perpendicular to the double-bubble structures; this is what we expect if the SSCs form in the dense collimating gas disk.

The inner parts of the dense gas disk should experience a significant dynamical effect from the superwind. While direct evidence of shocked gas in Arp 220 is not observed, we note that shocked regions are indeed observed in the nearer but less luminous nuclear starburst galaxy M82 (Lester et al. 1990). Although the actual gaseous matter in the nuclear region of Arp 220 is almost certainly clumpy, it is instructive to derive order-of-magnitude estimates of the dynamical effects of the superwind by considering the effects of a superwind propagating through a homogenous medium. The supernovae responsible for shocking the gas occur continuously over a timescale longer than or comparable to the dynamical timescale of the initial gas cloud, and the evolution of the shocked material can be described by a superbubble model (McCray & Snow 1979; Koo & McKee 1992a, 1992b; Heckman et al. 1996; Shull 1995; and references therein). The radius and velocity of the shocked shells that were formed in the dense gas disk at time $t$ are then

$$r_{\text{shell}} \sim 440L_{\text{mech,43}}^{-1/5}n_{H,4}^{-3/5}t_7^{3/5} \text{ pc}, \quad (1)$$

and

$$v_{\text{shell}} \sim 26L_{\text{mech,43}}^{-1/5}n_{H,4}^{-2/5}t_7^{-2/5} \text{ km s}^{-1}, \quad (2)$$

where $L_{\text{mech,43}}$ is the mechanical luminosity released collectively from the supernovae in units of $10^{43}$ ergs s$^{-1}$, $n_{H,4}$ is the average hydrogen number density of the interstellar medium (ISM) in the dense gas disk, assumed uniform, in units of $10^4$ cm$^{-3}$, and $t_7$ is the elapsed time since the onset of the superwind in units of $10^7$ yr. For Arp 220, recent observations suggest that $L_{\text{mech,43}} = 1$ (Heckman et al. 1996) and $n_{H,4} = 1$ (Scoville et al. 1991, 1997). Although we do not know the physical conditions of the nuclear gas disk in the recent past (i.e., $\sim 10^7$ yr ago), they may not be dramatically different from those observed currently. We therefore assume $n_{H} = 10^4$ cm$^{-3}$. In any case, the dependences on $n_{H}$ of both $r_{\text{shell}}$ and $v_{\text{shell}}$ are very weak (i.e., proportional to $n_{H}^{-3/5}$). Hence, if our assumed values of $n_{H}$ are incorrect by a factor of 2 or 3, the effects on the shell properties are very weak. In order to explain the spatial extension of the double-bubble structures, Heckman et al. (1996) estimated an age of the superwind, $t_7 \approx 3$, given a low-density ambient gas ($n_{H} \sim 10^{-2}$ cm$^{-3}$). Using this age, we obtain $r_{\text{shell}} \approx 800$ pc for the dense gas disk. This is approximately the extent of the SSCs.

Next we investigate the formation mechanism of the SSCs in the dense gas disk around the western nucleus. Gaseous fragments can grow gravitationally in the shocked shell that is formed by the dynamical effect of the superwind (cf. Whitworth
et al. 1994). Fragments that form within the shells experience a net inward acceleration due to self-gravity and a net outward acceleration due to the internal pressure. Whittworth et al. (1994) investigate the balance between these two accelerations and show that the timescale for the growth of the fastest growing fragments is $t_{\text{fastest}} \approx (2c_s^3/\rho G \Sigma)^{1/2}$, where $c_s$ is the sound speed in the shell and $\Sigma$ is its surface mass density. Nonlinear fragmentation in the shell then happens first at a time $t = t_{\text{fastest}}$. Noting that the surface mass density $\Sigma = C n_H m_H / \Sigma_{\text{shell}}$, where $C$ is a constant determined by the geometry ($C = 4/3$ for a sphere) and $m_H$ is the hydrogen atom mass, we then find that from equations (1) and (2), fragmentation within the shell first happens at a time $t \sim 5.7 \times 10^3 C^{1/2} n_{H,81}^{-1/2} M_{10}^{-1/2}$ yr at a radius $r_H \sim 81 L_{\text{mech,43}}^{1/2} n_{H,81}^{1/2} M_{10}^{-1/2}$ pc. Here $M_{10}$ is the Mach number when these fragments first appear in units of 10, equal to $c_{\text{shell}}/c_s$ (here it is assumed that $M_{10} \gg 1$; Whittworth et al. 1994). Estimating $c_s$ is difficult because the turbulent pressure in the shell is much greater than the thermal pressure. From equation (2), the shell is moving outward at a velocity $v_H$ when the fragments first appear, where $v_H \sim 81 L_{\text{mech,43}}^{1/2} n_{H,81}^{1/2} M_{10}^{1/2}$ km s$^{-1}$. Thus, $v_H$ is almost independent of $c_s$, so that our lack of knowledge of the sound speed is unimportant in determining the velocity of the shell when the fragments form. Following Whittworth et al. (1994), we can estimate the mass and size of the fragments:

$$M_f \sim c_s^2 (G n_H m_H v_H)^{1/2} \sim 7.9 \times 10^4 c_{s,10}^{7/2} n_{H,81}^{-1/2} v_{H,81}^{1/2} M_\odot,$$

and

$$l_f \sim c_s^3 (G n_H m_H v_H)^{1/2} \sim 5.4 c_{s,10}^{3/2} n_{H,81}^{-1/2} v_{H,81}^{1/2} \text{ pc},$$

where $c_s$ and $v_H$ are expressed in units of 10 and 81 km s$^{-1}$, respectively. We note that the local sound speed in the molecular gas clouds is $c_s \sim 0.5 T_{50}^{1/2}$ km s$^{-1}$, where $T_{50}$ is the temperature of molecular gas in units of 50 K. However, when we discuss the fragmentation in the shell, it is more reasonable to regard the random velocity of clouds as an effective sound speed—this bulk velocity is much larger than the local thermal velocity (e.g., 90 km s$^{-1}$ in Arp 220; Scoville et al. 1998). Therefore, the conclusion from this simple calculation is as follows: fragments of gas that grow gravitationally in the shocked shell are too small ($\sim 10^4 M_\odot$ and $\sim 5$ pc) to be the SSCs observed in Arp 220. Adopting a smaller sound speed (which is the main uncertainty in the above calculation) makes this statement even stronger.

Therefore, we have to look for another formation mechanism of the progenitor of SSCs. We consider the instability of the dense gas disk in the central region of Arp 220 because of its self-gravity. We draw on the results of Shlosman & Noguchi (1993), who investigated the general problem of the gravitational instability of nuclear gas disks in detail. They estimated the mass of a supercloud forming in such a disk as

$$M_{\text{sccl}} = \pi \left(\frac{\lambda_{\text{crit}}}{2}\right)^2 \Sigma_g,$$  \hspace{2cm} (3)

where $\Sigma_g$ is the surface mass density of the gas disk and $\lambda_{\text{crit}}$ is a typical scale length of the supercloud given by

$$\lambda_{\text{crit}} = \frac{2\pi^2 G \Sigma_p}{K^2}$$  \hspace{2cm} (4)

($K$ is the epicyclic frequency at the region where the gravitational instability occurs). Equations (3) and (4) can be expressed as

$$M_{\text{sccl}} \sim 5.7 \times 10^3 \Sigma_{p,4}^3 K_3^{-4} M_\odot,$$  \hspace{2cm} (5)

and

$$\lambda_{\text{crit}} \sim 8.5 \times 10^3 \Sigma_{p,4} K_3^{-2} \text{ pc},$$  \hspace{2cm} (6)

where $\Sigma_{p,4}$ is in units of $10^4 M_\odot$ pc$^{-2}$ and $K_3$ is in units of $10^3$ km s$^{-1}$ kpc$^{-1}$. Using the observed values of $\Sigma_g$ and $K$ (Scoville et al. 1998), we obtain masses of the superclouds up to $\sim 10^4 M_\odot$ (see Table 1). These are the masses of the gaseous clouds that will only equal the mass of forming stars, if the star formation efficiency is 1. Adopting a more reasonable efficiency of 0.1 from observations of the Galaxy, we derive a final stellar mass of $\sim 10^4 M_\odot$, which is consistent with observations (Shaya et al. 1994). As shown in Table 1, the masses of the gaseous clouds are less massive with increasing radius. Ongoing from 0.1 to 1 kpc, the clusters are approximately an order of magnitude smaller, assuming the same star formation efficiency everywhere. Despite the (large) uncertainty due to extinction, this trend is close to what is seen by Shaya et al. (1994; see their Tables 1 and 3).

Finally, we consider how the massive and large proto-SSC clouds that came from our stability analysis evolve into the more compact and less massive SSCs seen in the HST images. Once the superclouds are formed, they will collapse because of the effect of external pressure (Kimura & Tosa 1993). Given the hydrogen number density and the kinetic temperature of the superclouds, $n_H \sim 10^4$ cm$^{-3}$ and $T_{\text{kin}} \sim 10$ K, the pressure that is supported by the random motion of gas is $P_m \sim 2 \times 10^{-11}$ dyn cm$^{-2}$. Next we estimate the pressure of intersupercloud gas. Since the hot gas that is traced by soft X-ray emission is indeed associated with the nuclear region of Arp 220, it seems reasonable to assume that $T_{\text{kin}} \sim 10^7$ K (Heckman et al. 1996). However, there is no direct information on the intersupercloud gas density $n_{H,pc}$. Although there are considerable amounts of gas ($\sim 10^6 M_\odot$) in the nuclear region, most of this gas occurs in dense molecular clouds (Scoville et al. 1997). The only statement that we can make with any confidence about the density of intercloud gas is that it must be intermediate between the cloud density ($\sim 10^7$ cm$^{-3}$) and the density of the ambient coronal gas ($\sim 10^{-2}$ cm$^{-3}$; Heckman et al. 1996). A reasonable value is probably around 1 cm$^{-3}$, which is the typical gas density of the cold ISM in our Galaxy (Spitzer 1978, chap. 6, p. 131). The external pressure that is provided by the hot gas is then $P_m \sim 2 \times 10^{-7} (n_{H,pc} / 1 \text{ cm}^{-3})$ dyn cm$^{-2}$ for $T_{\text{kin}} \sim 10^7$ K. Therefore, the external pressure that is caused by the hot gas is higher than the internal one for any value of the

| $R$ (kpc) | $\Sigma_g$ (M$_\odot$ pc$^{-2}$) | $\kappa$ (km s$^{-1}$ kpc$^{-1}$) | $\lambda_{\text{crit}}$ (pc) | $M_{\text{sccl}}$ (M$_\odot$) |
|----------|-------------------------------|-------------------------------|---------------------------|---------------------------|
| 0.1      | 3.5 x 10$^4$                  | 3.6 x 10$^4$                  | 230                       | 1.45 x 10$^4$              |
| 0.3      | 0.8 x 10$^4$                  | 1.5 x 10$^4$                  | 302                       | 5.76 x 10$^3$              |
| 0.5      | 0.4 x 10$^4$                  | 1.0 x 10$^4$                  | 340                       | 3.65 x 10$^3$              |
| 1.0      | 0.1 x 10$^4$                  | 0.5 x 10$^4$                  | 340                       | 9.12 x 10$^2$              |
intercloud density higher than that of the coronal gas, and it is much higher (by a factor of 100) if \( n_H, IC \sim 1 \text{ cm}^{-3} \). Since the cooling timescale of neutral gas in the fragments, \( t_{\text{cool}} \sim 10^7 (n_H/10^3 \text{ cm}^{-3})^{-1} \text{ yr} \) (Spitzer 1978), is quite short, stars could form just after the fragmentation. The stars may form through the process of gravitational instability occurring inside the fragment. A typical length of the gravitational fluctuation (the Jeans length; Jeans 1929) is estimated to be \( \lambda_J \sim (\pi c_r^2/G \rho_{\text{gas}})^{1/2} \sim 1 \text{ pc} \), where \( \rho_{\text{gas}} = n_H m_H \). Therefore, since a typical mass of the fluctuation amounts to \( m \sim \lambda_J^3 \rho_{\text{gas}} \sim 100 M_\odot \), it is likely that the fluctuation will evolve into a massive star with a mass of \( \sim 10 M_\odot \). The single fragment (comprising these stars) experiences dynamical relaxation on a timescale of \( \tau_{\text{rel}} \sim 10^7 \text{ yr} \). The lifetime of these massive stars is \( \sim 10^7 \text{ yr} \). The single fragment (comprising these stars) experiences dynamical relaxation on a timescale of \( \tau_{\text{rel}} \sim 10^7 \text{ yr} \). The lifetime of these massive stars is \( \sim 10^7 \text{ yr} \). The single fragment (comprising these stars) experiences dynamical relaxation on a timescale of \( \tau_{\text{rel}} \sim 10^7 \text{ yr} \). The lifetime of these massive stars is \( \sim 10^7 \text{ yr} \).

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