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CLEARING THE DUST FROM GLOBULAR CLUSTERS

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ABSTRACT

Recent *Spitzer* observations of the globular cluster M15 detected dust associated with its intracluster medium. Surprisingly, these observations imply that the dust must be very short-lived compared to the time since the last Galactic plane crossing of the cluster. Here we propose a simple mechanism to explain this short lifetime. We argue that the kinetic energy of the material ejected during a stellar collision may be sufficient to remove the gas and dust entirely from a cluster, or to remove the gas as a wind, in addition to partially destroying the dust. By calculating the rate of stellar collisions using an *N*-body model for the cluster, we find remarkable agreement between the average time between collisions and the inferred dust lifetime in this cluster, suggesting a possible close relation between the two phenomena. Furthermore, we also obtain the birthrate of blue stragglers formed through collisions in M15. By comparing with the observed number of blue stragglers, we derive an upper limit for their average lifetime that turns out to be consistent with recent model calculations, thereby lending further support to our model.

Subject headings: blue stragglers — globular clusters: general — globular clusters: individual (M15) — shock waves — stars: mass loss — stellar dynamics

1. INTRODUCTION

In recent years, infrared space telescopes such as *IRAS, ISO*, and especially *Spitzer* made it possible to investigate not only the stellar content of globular clusters (GCs) but also their intracluster medium (ICM), consisting of gas and dust lost by giants. Evans et al. (2003) were the first to clearly detect thermal dust emission from the core of the GC M15 (NGC 7078) with *ISO*. They found a dust mass an order of magnitude lower than one would expect based on the number, mass-loss rates, and lifetimes of horizontal branch (HB) stars, even at the extremely low metallicity of M15. Subsequent, more sensitive measurements with *Spitzer* resulted in a dust mass of $9 \times 10^{-4}\ M_\odot$, indicating an accumulation time span not much longer than 10^6 yr (Boyer et al. 2006). While such a short time is commonly explained by ram pressure stripping during Galactic plane passages, the time since the last passage for M15 is about 4×10^7 yr, an order of magnitude larger. Therefore, additional processes have been suggested to explain short ICM lifetimes, including blowout of nova explosions, fast winds from stars, relativistic winds from millisecond pulsars (Spergel 1991), and radiative ejection by the strong radiation field in M15 (Smith 1999).

Another possibility that has not yet been investigated is related to the outcome of stellar collisions. From hydrodynamic simulations it is known that colliding main-sequence stars (MSS) lose typically ~1% of their mass (see, e.g., Lombardi et al. 1996). As this material is ejected with speeds typically a few times the escape speed from the stellar surface, it will transfer a significant amount of energy to the ICM and possibly reduce the amount of observable dust considerably. For instance, if the gas, released through a collision between two $0.5\ M_\odot$ MSSs, has a mass of $0.02\ M_\odot$ and leaves with twice the escape velocity (≈ 1200 km s^{-1}), it possesses enough kinetic energy to accelerate more than $15\ M_\odot$, the estimated total mass of ICM gas in M15 (Boyer et al. 2006), up to a speed of 40 km s^{-1}, the escape speed from the center of M15.

The inferred dust lifetime in the ICM would then require that such a stellar collision happens every ~1 Myr. Given that M15 has a central density of $n \gtrsim 10^6\ M_\odot\ \mathrm{pc}^{-3}$ and a velocity dispersion of $\sigma \approx 10$ km s^{-1} (see, e.g., McNamara et al. 2004), the collision time

$$T_{\mathrm{coll}} = 7 \times 10^{11}\ \mathrm{yr} \left(\frac{10^5\ \mathrm{pc}^{-3}}{\nu}\right) \left(\frac{\sigma}{100\ \mathrm{km\ s}^{-1}}\right)$$

for a $1\ M_\odot$ MSS is $\sim 10^{10}$ yr (Binney & Tremaine 1987). This results in at least one collision every <5 Myr for the more than 2000 stars in the core (e.g., Dull et al. 1997). From this rough estimate one can already see that this mechanism is indeed promising.

However, there are several factors in M15 that complicate a better estimate of the collision time. First, in GCs as old as M15, all MSSs have masses below $0.8\ M_\odot$, while initially more massive stars have produced remnants such as white dwarfs (WDs) and neutron stars (NSs), which will have different interaction rates. Second, because of mass segregation, the lower mass MSSs may concentrate in lower density regions, while more massive WDs and NSs concentrate near the center. Finally, it is not a priori clear that enough energy from the gas ejected in a stellar collision can be effectively transferred to the ICM since losses through radiative shocks may be important.

We address the issue of mass segregation considering a specific model of M15 given in McNamara et al. (2004), which is based on an *N*-body model of Baumgardt & Makino (2003). This allows us to estimate collision times involving different stellar populations in the cluster. Furthermore, we obtain a minimum formation rate for blue stragglers (BSs) through MS-MS mergers. Using the number of observed BSs in the core of M15, we estimate an average BS lifetime and compare it with evolutionary models, as an extra check on our basic model (§ 2). In § 3 we discuss how the ejected material from a stellar collision interacts with the ICM and how it can clear signatures of dust emission. We conclude in § 4.

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2. COLLISION TIMES

We define a collision between two stars with radii R_1 and R_2 to occur whenever their distance $d \leq R_1 + R_2$. The average local collision time $T_{\rm coll}^{(1,2)}(r)$ for one star of type 1 to collide with a star of type 2 can be written as (compare to Binney & Tremaine 1987, their eq. [8-122])

$$\frac{1}{T_{\rm coll}^{(1,2)}(r)} = 4\sqrt{\pi} n_2(r)\sigma(r) \times \left[(R_1 + R_2)^2 + \frac{G(M_1 + M_2)(R_1 + R_2)}{2\sigma(r)^2}\right], \quad (1)$$

where $n_{1,2}$ is the number density of field stars of types 1 and 2, $M_{1,2}$ their masses, and σ the one-dimensional velocity dispersion (assuming a Maxwellian velocity distribution for both species with $\sigma(r) = \sqrt{[\sigma_1(r)^2 + \sigma_2(r)^2]/2}$). To get the total number of collisions per unit time in the cluster between these two species, equation (1) is integrated over the whole cluster,

$$\frac{dN_{\rm coll,tot}}{dt} = 4\pi \int_0^\infty dr\, r^2 n_1(r) \frac{1}{T_{\rm coll}(r)}, \quad (2)$$

where r is the radial position in the cluster.

In order to account for a continuous stellar mass spectrum and the mass-radius relationship of stars, we take local averages $R_{1,2}(r)$ and $M_{1,2}(r)$ at position r. We find that in the N-body model for M15 these profiles, as well as $n_{1,2}(r)$, can be well represented by power laws over a sufficiently large range of $0.025\ {\rm pc} < r < 2$ pc. Inside of 0.025 pc there are almost no MSSs, while outside of $\approx$1 pc the contribution of the integrand in equation (2) becomes rapidly negligible. We do not consider collisions between MSSs and NSs as the NS retention fraction in GCs is expected to be low (Pfahl & Rappaport 2002; Dull et al. 1997). We also do not consider collisions between giants and MSSs as the escape velocity at the surface of a giant, and even more so the expected energy of the ejected material, is an order of magnitude lower than for MSSs. For simplicity we choose a constant $\sigma = 11\ {\rm km\ s^{-1}}$, as σ does not vary much within 1 pc ($\pm 1\ {\rm km\ s^{-1}}$; compare Dull et al. 1997) and also agrees with the value obtained by McNamara & Baumgardt (2004) for M15 for a similar region ($r < 0.3' \approx 0.8$ pc). The slight variations within 1 pc are accounted for in the error estimates of the collision rates. With all quantities given as power laws, we solve equation (2) analytically. Our calculations are based on the results of N-body simulations by Baumgardt & Makino (2003), which were scaled to fit the velocity dispersion profile of M15 in McNamara et al. (2004). Their model consisted of initially 130,072 stars with a realistic mass spectrum and included a treatment of stellar evolution and the Galactic tidal field. They also take into account velocity kicks imparted to NSs at birth and consider two extreme cases: one where all NSs are retained and one where all NSs are removed from the cluster. Here we consider only the latter case, since, as mentioned before, the actual NS retention fraction is expected to be very low.

In Table 1 the fit parameters for n, R, R^2, and M for WDs and MSSs in M15 are shown. As can be seen, through mass segregation, MSSs are more abundant outside 1 pc while the more massive WDs dominate the central 0.75 pc where collisions are most likely to happen. As a consequence, we should expect more collisions between WDs and MSSs than between MSSs. From equation (2), we obtain $dN_{\rm coll,MS\text{-}WD}/dt = (2 \pm 1) \times 10^{-7}\ {\rm yr^{-1}}$ and $dN_{\rm coll,MS\text{-}MS}/dt = (4 \pm 1) \times 10^{-8}\ {\rm yr^{-1}}$, where $N_{{\rm coll},X\text{-}Y}$ is the number of collisions between X and Y. It follows that, given the current state of M15, we expect one collision every $(5 \pm 2) \times 10^6$ yr between a WD and a MSS and every $(3 \pm 1) \times 10^7$ yr a collision between two MSSs, resulting in one collision every $(4 \pm 2) \times 10^6$ yr that releases high-velocity gas into the ICM. It is rather remarkable how closely this timescale coincides with the estimated ICM dust lifetime, suggesting a direct connection between dust clearing and stellar collisions.

TABLE 1

Parameters of the Power-Law Fits for the Mass (M), Density (n), and Stellar Radius (R) for WDs and MSSs

	a_0	b
$n_{\rm MS}$	$(3.9 \pm 0.2) \times 10^3\ {\rm pc^{-3}}$	-1.620 ± 0.006
$n_{\rm WD}$	$(3.3 \pm 0.1) \times 10^3\ {\rm pc^{-3}}$	-2.280 ± 0.009
$R_{\rm MS}$	$(0.51 \pm 0.05)\ R_\odot$	-0.143 ± 0.008
$R^2_{\rm MS}$	$(0.32 \pm 0.05)\ R_\odot$	-0.26 ± 0.01
$M_{\rm MS}$	$(0.49 \pm 0.02)\ M_\odot$	-0.105 ± 0.002
$M_{\rm WD}$	$(0.74 \pm 0.02)\ M_\odot$	-0.117 ± 0.002

Note.—The power laws are of the form $a = a_0 (r/r_0)^b$ with $r_0 = 1$ pc.

Using a similar approach, we estimate the BS formation rate, defining BSs as two merged MSSs with a combined mass $>1\ M_\odot$, significantly larger than the MS turnoff mass ($0.8\ M_\odot$). After binning all MSSs into $0.1\ M_\odot$ bins, we determine the collision rate between all mass bins with combined mass $>1\ M_\odot$. This also allows us to determine the expected mass spectrum for BSs for comparison with future observations. We obtain a total collision rate of $(6.4 \pm 0.7) \times 10^{-3}\ {\rm Myr^{-1}}$, which, together with the six or seven BSs observed in M15, implies an average BS lifetime of about 1 Gyr. This is also consistent with recent BS evolution models (e.g., Leigh et al. 2007; Sills et al. 2001). However, we note that this is certainly an upper limit, given that the presence of binaries would increase the formation rate through binary mergers and resonant interactions (Fregeau et al. 2004; Mapelli et al. 2004). For example, for a Plummer sphere with a Kroupa mass function ranging from 0.3 to 3.0 $M_\odot$ and a binary fraction of 30%, the rate of collisions mediated by binary-single and binary-binary interactions can be $\sim$1 order of magnitude larger than that from single-single interactions (Chatterjee et al. 2008). In Figure 1 the mass distribution for BSs is shown. As expected, it decreases for higher mass BSs, since the number density for the lower mass MSSs is much higher compared to that for the close to turnoff MSSs.

3. INTERACTION OF COLLISION EJECTA WITH THE ICM

Interactions between very fast moving gas and a low-density interstellar ambient medium have been extensively investigated in the context of supernova remnants. Their evolution progresses in several distinct stages (Chevalier 1977): the "ejecta dominated" (ED) stage, characterized by a freely expanding blast shock wave until the mass of the swept-up material is comparable to the mass of the ejecta; the "Sedov-Taylor" (ST) stage, where the blast wave expands adiabatically; and the "pressure-driven snowplow" (PDS) stage, where a thin shell forms that "snowplows" through the ambient medium, driven by the pressure of the hot interior in addition to its own momentum (Cox 1972; Cioffi et al. 1988). Cioffi et al. (1988) obtained a simple offset power-law solution that describes the kinematics of the blast wave in the PDS stage, which can be written as $v_s = v_{\rm PDS}(R_s/R_{\rm PDS})^{-7/3}$, where v_s and R_s are the ve-

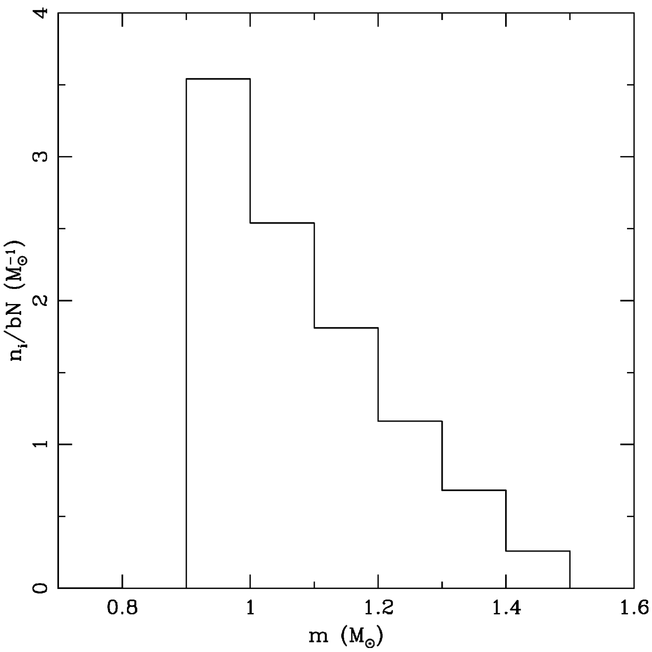

FIG. 1.—Estimated mass distribution of BS candidates created via collisions between two MSSs with combined mass >0.8 $M_\odot$. n_i, b, and N are the number of BSs in the ith bin, the bin size, and the total number of BSs, respectively.

locity and radial position of the shock front, respectively, relative to the site of the collision, and $v_{\rm PDS}$ and $R_{\rm PDS}$ are the velocity and radial position of the shock front at the transition from the ST stage to the PDS stage. The transition values are given by $v_{\rm PDS} = 413 n_0^{1/7} \zeta_m^{3/14} E_{51}^{1/14}$ km s^{-1} and $R_{\rm PDS} = 14.0 E_{51}^{2/7} \zeta_m^{-1/7} n_0^{-3/7}$ pc, where E_{51} is the kinetic energy of the ejected material in units of 10^{51} ergs, n_0 the density of the ambient medium in cm^{-3}, and ζ_m the heavy-element abundance relative to solar abundances. An interesting property of the flow of the postshock gas is that in the PDS stage its mean velocity has the same value as the shock speed (Cioffi et al. 1988). For our problem this means that, provided v_s is larger than the cluster escape speed after the shock swept up all of the ICM, the shocked gas can entirely escape the cluster.

It is now interesting to see if such an ICM removal mechanism might be applicable to M15. For this estimate we assume an ICM mass of 15 $M_\odot$, which is expected given the amount of dust detected by Boyer et al. (2006) and the low metallicity of M15 ($\zeta_m = 10^{-2.4}$). In order to estimate E_{51} for collisions between MSS, we can use the results of Lombardi et al. (2002) (their Table 3), obtaining $E_{51} = (1\text{–}11) \times 10^{-4}$. Unfortunately, there are no similar results for MS-WD collisions. However, given that the mass loss is presumably between 15% and 50% (Ruffert & Mueller 1990; Ruffert 1992) and that the velocity of the ejecta should be of the order of the escape speed of the MSS (≈500 km s^{-1}), we obtain a similar range for E_{51}. Note that, although the ejecta are ejected nearly isotropically (Lombardi et al. 1996), the ICM is likely to have a more irregular structure, as the patchy dust emission in M15 indicates. Thus, only a fraction of the released energy might actually be transferred to the ICM. As the 3D structure of the ICM is unknown, we limit our analysis to a fiducial ejecta energy of $E_{51} = 3 \times 10^{-4}$ but also determine the minimum E_{51} value to remove all of the ICM gas from the cluster, noting that these values are to be understood as "effective" energies ramming into the ICM gas. Similarly, estimates for the ICM density are also rather uncertain. If we assume that all the gas is contained within a radius of 1–2 pc (the approximate radial position of the dust emission), the density of a 15 $M_\odot$ gas cloud would be between 20 and 150 cm^{-3}. For simplicity, we also assume that the shock, once it leaves the ST stage, remains radiative, which might not necessarily be the case for the low temperatures ($T < 10^5$ K) and shock speeds (<50 km s^{-1}) when the shock has swept up most of the ICM, as cooling is less efficient in this regime (Sutherland & Dopita 1993).

Using $E_{51} = 3 \times 10^{-4}$ and $n = 20\text{–}150$ cm^{-3} we obtain $v_s \approx 13\text{–}15$ km s^{-1} after the shock has swept up 15 $M_\odot$. Since this velocity is lower than the escape speed of ≈40 km s^{-1} for M15, it follows that the energy of the ejected material from one MSS collision may not be sufficient to remove the ICM completely. In fact, only for $E_{51} \gtrsim 8 \times 10^{-4}$, which is at the upper end of the estimated ejecta energy interval, does the shocked ICM gas attain a velocity sufficiently large to leave the cluster.

On the other hand, the shock also heats up the gas to high temperatures, [≈(10–15) × 10^4 K at those shock speeds]. Gas at such temperatures expands beyond a critical radius and flows out of the cluster as a wind, reducing the amounts of ionized gas down to less than 1 $M_\odot$ (Knapp et al. 1996). Assuming that the dust follows the gas, the dust would therefore leave the cluster on a timescale as short as ~10^5 yr. In fact, the wind should be even stronger in our scenario than for the static model considered in Knapp et al. (1996), since here the gas itself has a considerable outward speed through the shock.

So far, we assumed the existence of rather large amounts of gas, based on the amount of observed dust and M15's extremely low metallicity. However, searches for gas in M15 have had very limited success, and Smith et al. (1995) estimate an upper limit for the total ICM mass of about 3 $M_\odot$. The reason for the much larger observed dust-to-gas ratio is not well understood (see, e.g., van Loon et al. 2006). As the dust-to-gas ratio of the material lost in the winds of red giants should scale with the metallicity of the stars (van Loon et al. 2005), thus resulting in more than 10 $M_\odot$ of gas, it appears that additional processes may be at work that remove the gas more easily than the dust. Nevertheless, it is also possible that most of the ICM is in molecular form as the CO-to-H_2 conversion factor is not known for such low metallicities and extreme radiative environments (van Loon et al. 2006). Repeating the previous calculation for an ICM mass of $M = 3\ M_\odot$ and $n = 3\text{–}30$ cm^{-3} accordingly, we obtain $v_s = 52\text{–}63$ km s^{-1} for $E_{51} = 3 \times 10^{-4}$, while for $E_{51} = 2 \times 10^{-4}$ we obtain $v_s = 39\text{–}47$ km s^{-1}, which is close to and larger than the cluster escape speed of 40 km s^{-1}. In this case, the ejecta of one MSS collision would likely be able to accelerate this gas out of the cluster.

As a final caveat, we note that it is not very clear whether the dust will follow the rather low-density ionized gas. This strongly depends, among other quantities, on the dust grain properties and their electric potential relative to the ionized gas in a rather complicated way (Draine & Salpeter 1979). For instance, Nozawa et al. (2006) and similarly Slavin et al. (2004) found in their simulations of shocks driven into dusty interstellar medium that while small grains with sizes of ≈0.01 μm get destroyed by sputtering and grain-grain collisions, only grains with sizes ≈0.1 μm are actually dragged along with the gas, while grains with sizes ≥1 μm remain almost unaffected and do not follow the shock wave. On the other hand, if the size distribution of the dust grains is similar to the one for the local interstellar medium, we see (e.g., Mathis 1996) that most of the dust mass is in grains with sizes of ≈0.1 μm. This means that, even if not all dust particles follow the gas flow, we can nevertheless expect that most of the dust mass will remain sufficiently well coupled to the gas and consequently be removed.

4. CONCLUSIONS

In this Letter we proposed a new mechanism to explain the relatively short lifetimes of the ICM dust in a dense GC, developing our arguments in detail for the case of M15. By calculating the rate of stellar collisions using the detailed model for M15 by McNamara et al. (2004), we find a remarkable, close agreement between the average time between collisions and the inferred dust lifetime of $\simeq 10^6$ yr (Boyer et al. 2006) in this cluster, pointing to a direct link between the two phenomena. We argue that the kinetic energy of the material ejected during a stellar collision may be sufficient to remove the dust from the cluster, depending on the assumed ICM mass, either directly by accelerating dust and gas to velocities larger than the cluster escape speed or indirectly by accelerating and heating the gas, which then expands and leaves the cluster as a wind, carrying the dust along with it. Although there are some uncertainties as to how well the dust will couple to the gas, especially at the low shock speeds expected for this problem, there are some indications from simulations of supernova remnants that might support sufficient coupling (e.g., Nozawa et al. 2006). In addition, at least some dust grains can also be efficiently destroyed by grain-grain collisions or sputtering (Slavin et al. 2004; Nozawa et al. 2006), which further helps to reduce the amount of observable dust in the cluster. On the other hand, the results of these studies may not be directly applicable to our scenario because, e.g., the intense UV field present in a cluster like M15 could strongly affect the electric potential of the grains and, therefore, their coupling to the ionized gas (Draine & Salpeter 1979).

With a detailed model for M15 we were also able to calculate the formation rate and mass distribution of BSs through MS-MS collisions. By comparing with the observed number of BSs in the cluster, we derive an upper limit to their average lifetime of $\simeq 1$ Gyr, consistent with current stellar structure and evolution models for BSs (e.g., Leigh et al. 2007).

We conclude that the interaction of ejected gas from stellar collisions with the ICM will strongly influence the observable signal of the dust in the ICM, and given the remarkable agreement between dust lifetimes and collision times in M15, this represents a promising mechanism to explain the very short dust and ICM lifetimes in GCs.

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