AN ARC OF YOUNG STARS IN THE HALO OF M82

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Received 2008 January 23; accepted 2008 March 25; published 2008 April 14

ABSTRACT

The properties of the brightest resolved stars in an arc that was originally identified by Sun et al. and is located in the extraplanar regions of M82 are discussed. The stars form an elongated structure that is traced over a projected area of $3.0 \times 0.8$ kpc$^2$. The integrated brightness is $M_V \sim -11$, while the total stellar mass is between $3 \times 10^8$ and $2 \times 10^9 \, M_\odot$. If there is only foreground extinction then the youngest stars have a metallicity $Z \geq 0.008$ and an age $0.8 \, \text{Myr}$; thus, the youngest stars formed at roughly the same time as stars in tidal features that are associated with other M81 Group galaxies. If the arc disperses then it will deposit young, chemically enriched stars into the M82 halo.

Subject headings: galaxies: evolution — galaxies: halos — galaxies: individual (M82) — galaxies: starburst

1. INTRODUCTION

As one of the closest galaxy groups, the M81 Group is an important laboratory for probing galaxy evolution. Unlike the Local Group, the M81 Group contains galaxies that have experienced cosmologically recent interactions, with the elevated levels of star formation in M82 and NGC 3077 likely triggered by an encounter with M81 within the past few hundred million years (Brouillet et al. 1991; Yun et al. 1994). Subsequent studies of the stellar fossil record in M82 have since found evidence of widespread elevated levels of star-forming activity roughly 0.5–1 Gyr in the past (e.g., de Grijs et al. 2001; Mayya et al. 2006). More recent episodes of star-forming activity have been restricted to the inner regions of M82 (e.g., Gallagher & Smith 1999; Forster Schreiber et al. 2003; Smith et al. 2006).

The interactions in the M81 Group have had a major impact on the intracluster environment. Feedback from supernovae power an outflow from M82 that injects chemically enriched material into the intracluster medium (e.g., Shopbell & Bland-Hawthorn 1998), which in turn may interact with surrounding clouds (e.g., Devine & Bally 1999). Tidal interactions can also pull material from galaxies, and morphological signatures of this activity are seen near some M81 Group galaxies (e.g., Karachentseva et al. 1985). The molecular material in M82 has been severely disrupted (Walter et al. 2002), and the morphology of the galaxy has been affected; while it now has an amorphous appearance, there are indications that it may have been a late-type spiral or irregular galaxy before the encounter with M81 (e.g., O’Connell & Mangano 1978).

Sun et al. (2005) find an arclike feature in the southern regions of M82, which they refer to as ‘‘M82 South.’’ This object has a flat spectral energy distribution (SED) at visible wavelengths, a relatively high surface brightness, and is also seen in the UV (Fig. 2 of Hoopes et al. 2005). M82 South is located just outside of the region imaged for the M82 Surveys Mosaic with the HST ACS (Mutchler et al. 2007). It can be anticipated that at least some of the light from M82 South originates from young stars, and resolving stars in such a feature would be of great interest. The light that has been detected

2. OBSERVATIONS

The data were obtained with the MegaCam imager (Boulade et al. 2003) on the 3.6 m Canada-France-Hawaii Telescope (CFHT) as part of a wide-field survey of M81 and M82. The detector in MegaCam is a mosaic of 36 $2048 \times 4612$ pixel$^2$ CCDs, and each exposure covers roughly 1 degree$^2$ with 0.185$''$ pixel$^{-1}$. Four 360 s exposures were recorded through $r'$ and $i'$ filters with the midpoint between M82 and M81 centered on the detector mosaic. Stars in the final images have 0.8$''$ FWHM in $r'$ and 0.7$''$ FWHM in $i'$.

The raw data were processed with the ELIXER package at the CFHT, and this included bias subtraction, flat-fielding, and fringe removal. The reduced images were then aligned and combined by the author at the HIA. The photometric measurements were made with ALLSTAR (Stetson & Harris 1988), using a point-spread function (PSF) constructed with the DAO-PHOT (Stetson 1987) PSF routine. The photometric calibration is based on the zero points that are placed in MegaCam data headers as part of the ELIXER processing. These zero points are calculated from standard star observations that are recorded as part of the MegaCam queue observing process.

1 Based on observations obtained with the MegaPrime/MegaCam, a joint project of the CFHT and CEA/DAPNIA, at the Canada-France-Hawaii Telescope (CFHT), which is operated by the National Research Council (NRC) of Canada, the Institut National des Sciences de l’Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii.
3. RESULTS

3.1. The Morphology and Integrated Brightness of M82 South

M82 South was discovered independently by the author when the locations of stars that were photometered with DAOPHOT were plotted (T. J. Davidge 2008, in preparation). A section of the final $i'$ MegaCam image that includes M82 South is shown in Figure 1. An expanded view of the region near M82 South is shown in the lower right hand corner of Figure 1, while the spatial distribution of sources in this same area is shown in the left-hand inset. The regions used in the analysis that sample the main concentration of stars in M82 South and the background/control fields are indicated.

To estimate an upper mass limit $M/L_V = 1$ was assumed, and the total mass in this case is $(2 \pm 1) \times 10^8 M_\odot$.

3.2. Stars in M82 South

The $(i', r' - i')$ CMDs of objects within $\pm 20''$ of the M82 South ridgeline are shown in the middle row of Figure 2. The CMDs of the background/control fields indicated in Figure 1 are also shown. The control fields to the northeast and southwest of M82 South contain very different numbers of stars, due to the gradient in stellar density in the outer regions of M82, and this gradient makes it difficult to place the northern boundary of M82 South with confidence. With the caveat that the northern control field may contain some stars belonging to M82 South, then it appears that no more than one third of the sources within $\pm 20''$ of the M82 South ridgeline do not belong to M82 South.

Contamination from foreground Galactic stars, background galaxies, and stars in the M82 field can be accounted for statistically by assessing the color and brightness distributions of objects in M82 South. The net $r' - i'$ color function of sources with $i'$ between 23.5 and 24.5 ($M_i \sim -4.5$ to $-3.5$) in the control fields from the color distribution of sources in M82 South is shown in the top panel, where $N_{r'i'}$ is the net number of stars in this brightness interval per 0.1 mag $r' - i'$ interval. Note that the color distribution runs from $r' - i' = 0.3$ to 0.5, with a peak near $r' - i' \sim 0$. The LF that results from subtracting the mean LF of the control fields from the LF of M82 South is shown in the bottom panel, where $N_{r'i'}$ is the net number of stars per 0.5 mag $i'$ interval. Note that the majority of stars in M82 South have $i' \geq 23.0$, which corresponds roughly to $M_i \geq -6$. The $[M_i, (r' - i')]_0$ CMD of stars within $\pm 20''$ of the M82
South ridge line is shown in Figure 3. A distance modulus of 27.95 (Sakai & Madore 1999) has been adopted, with a foreground reddening $A_v = 0.10$ (Burstein & Heiles 1984). There is dust in the M82 outflow (e.g., Heckman et al. 1990), and so the foreground reddening is a lower limit to the actual reddening. This being said, M82 South is much further from the disk plane than the area where dust has been detected. Furthermore, the mean colors and color distributions of stars in the eastern and western portions of M82 South are not different, indicating that if dust is present then it is very uniformly distributed.

Also shown in Figure 3 are evolutionary tracks from Girardi et al. (2004) with $Z = 0.008$ and 0.019 for ages $\log(t_p) =$ 7.5 and 8.0. While not shown in Figure 3, isochrones with $Z = 0.0001$ place the red supergiant locus at $r' - i'$ colors that are $\pm 0.2$–0.3 smaller than those with $Z = 0.008$. With the caveat that up to one-third of the stars probably do not belong to M82 South, then the red envelope of stars in Figure 3 argues for $Z \geq 0.008$, which is consistent with the metallicity of young stars in the disk of M82 (e.g., Mayya et al. 2006). The stars in M82 South thus formed from chemically enriched gas.

The ages of the youngest stars can also be estimated from the isochrones in Figure 3. The large number of stars with $M_i$ between $-4$ and $-5$ and $r' - i'$ between $-0.1$ and 0.3 is consistent with $\log(t_p) =$ 7.75–8.0; thus, $\log(t_p) =$ 7.75 is adopted for the youngest stars. An interesting check of this age comes from a comparison with Holmberg IX, which has an SED at visible wavelengths that is very similar to that of M82 South (Sun et al. 2005). Makarova et al. (2002) find that the majority of stars in Holmberg IX have ages $\log(t_p) =$ 7.8, in excellent agreement with what is found in M82 South.

### 4. Discussion

Deep images obtained with the CFHT MegaCam have been used to resolve individual stars in M82 South. The youngest stars have ages $\log(t_p) =$ 7.75 and $Z \geq 0.008$. Thus, despite having a projected distance of $\sim 6$ kpc off of the M82 disk plane, M82 South recently formed stars from chemically enriched material.

Lacking kinematic information, the physical separation between M82 South and the main body of M82 is a matter of speculation. M82 South is not in the disk plane of M82, and it seems likely that M82 South is associated with the extraplanar regions of M82, as opposed to being an outlying structure on the far or near side of the M81 Group, given its close projected proximity to M82. The general morphology of M82 South in Figure 4 of Sun et al. (2005) is reminiscent of the filamentary features that originate from M81, albeit on a much smaller scale. Thus, M82 South physically resembles features seen in the outer regions of other galaxies.

Adopting the mass estimates in § 3 then it is unlikely that M82 South will be a long-lived feature. If the mass of M82 is $10^{10} M_\odot$ (Sofue et al. 1992), then the tidal radius of M82 South is a few tenths of a kpc if the projected separation of 6 kpc corresponds to the actual separation. To escape tidal pruning, M82 South would have to be 50–100 kpc away from M82, on the side of M82 that is farthest from M81. If it is within 10–20 kpc of M82 then M82 South will survive for only a few orbital crossing times about M82, or $\sim 10^4$ yr, depending on the actual distance from M82 and the nature of the orbit about the larger galaxy.

Could M82 South be the remnant of a preexisting dwarf galaxy that was disrupted by M82? This is unlikely, as the metallicity of stars in M82 South suggest that such a satellite would have had an LMC-like mass, which is roughly 25%–50% that of M82. The disruption of such a massive galaxy would leave significant tidal debris trails, which are not seen.

There are conspicuous signatures of galaxy–galaxy interactions throughout the central regions of the M81 Group. Gas bridges link galaxies (e.g., Yun et al. 1994; Boyce et al. 2001), and there are objects that may be tidal dwarfs (Karachentsev et al. 2002; Makarova et al. 2002). Could M82 South be such a tidal fragment? The youngest stars in M82 South have ages near 50 Myr, and there was contemporaneous star formation in other candidate tidal features, such as Holmberg IX, the Garland, and the Arp Loop (e.g., Makarova et al. 2002; Sakai & Madore 2001). However, tidal dwarfs are predicted to be gas-rich (e.g., Barnes & Hernquist 1992), and the H I map of Yun et al. (1994) does not show an H I concentration near M82 South, which is in marked contrast to Holmberg IX and the Arp Loop. This being said, the presence of diffuse Hα emission (Fig. 2 of Hoopes et al. 2005) suggests that M82 South may not be completely devoid of gas.

The outflow from M82 has ejected at least $3 \times 10^4 M_\odot$ of gas out of the disk plane (Walter et al. 2002), and M82 South may have condensed out of some of this material. The “Cap” (Devine & Bally 1999) is located some 11 kpc to the north of the M82 disk plane, and is thought to have formed in a shock that occurred when the outflow encountered clouds surrounding M82 (e.g., Lehnert et al. 1999; Strickland et al. 2004). The material in the Cap is metal-enriched (e.g., Hoopes et al. 2005; Strickland & Heckman 2007; Tsuru et al. 2007), and there are knots that may indicate the onset of star formation, although stars have yet to be resolved. If M82 South is a related structure then it must be in a later stage of evolution. M82 South is a much weaker source of X-ray (e.g., Tsuru et al. 2007) and Hα.
(Hoopes et al. 2005) emission than the Cap, but is a source of much stronger UV emission, which is concentrated in at least three knots (Hoopes et al. 2005). While the absence of detectable X-ray emission indicates that the material in M82 South is not at present experiencing shock excitation, such activity in the past might have triggered star formation. The drop in stellar density that defines the western edge of M82 South might then mark the spatial extent of star-forming material.

If M82 South is a genuinely young object then it will not have an underlying population of old stars. Deep high angular resolution imaging will provide constraints on whether or not stars evolving on the red giant branch are present; if such stars are detected then they would indicate an age of at least \( \sim 1 \) Gyr for M82 South. The detection of such stars would also suggest that M82 South is probably more distant from M82 than 6 kpc, given the disruption time estimated above.

We conclude by noting that if structures like M82 South are common in interacting galaxies then they may have a significant impact on the extraplanar stellar content of these objects. If M82 South is dispersing then its young metal-rich stars may eventually migrate into the extraplanar regions of M82 or the intragalactic medium in the M81 Group. If similar structures have formed previously and dispersed near M82 then deep imaging of the outer regions of M82 should reveal stars with a wide range of ages and metallicities. The CMDs of the northeast control field in Figure 2 and in the extraplanar regions of other galaxies (e.g., Mouhcine 2006) suggest that such a dispersion in stellar content is present.

Sincere thanks are extended to Brenda Matthews for discussions regarding the role of shocks in star formation. It is also a pleasure to thank the anonymous referee for providing comments that greatly improved the manuscript.

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