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A SPECTACULAR Hα COMPLEX IN VIRGO: EVIDENCE FOR A COLLISION BETWEEN M86 AND NGC 4438 AND IMPLICATIONS FOR THE COLLISIONAL ISM HEATING OF ELLIPTICALS

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ABSTRACT

Deep wide-field Hα+[N ii] imaging around the Virgo Cluster giant elliptical galaxy M86 reveals a highly complex and disturbed ISM/ICM. The most striking feature is a set of Hα filaments which clearly connect M86 with the nearby disturbed spiral NGC 4438 ($23' = 120$ kpc projected away), providing strong evidence for a previously unrecognized collision between them. Spectroscopy of selected regions shows a fairly smooth velocity gradient between M86 and NGC 4438, consistent with the collision scenario. Such a collision would impart significant energy into the ISM of M86, probably heating the gas and acting to prevent the gas from cooling to form stars. We propose that cool gas stripped from NGC 4438 during the collision and deposited in its wake is heated by shocks, ram pressure drag, or thermal conduction, producing most of the Hα filaments. Some Hα filaments are associated with the well-known ridge of bright X-ray emission to the NW of the nucleus, suggesting that the collision is responsible for peculiarities of M86 previously ascribed to other effects. M86 is radio-quiet; thus AGN heating is unlikely to play a significant role. The M86 system has implications for understanding the role of gravitational interactions in the heating of the ISM in ellipticals, and how collisions in clusters transform galaxies.

Subject headings: cooling flows — galaxies: clusters: individual (Virgo) — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: interactions — galaxies: ISM

1. INTRODUCTION

The warm ionized plasma of elliptical galaxies is an important phase of the ISM that traces evolutionary processes and galactic interactions. Hα emission from this ISM phase has been observed in many ellipticals (Trinchieri & de Serego Alighieri 1991; Macchetto et al. 1996), and has sometimes been interpreted to be the result of "cooling flows," in which the hot X-ray emitting plasma radiates, cools down, and sinks toward the galactic center (Fabian 1994). However, since the mass in colder gas and newly formed stars in most galaxies is far less than simple cooling models predict (Peterson et al. 2003), a heating source is required to limit the net cooling rate. Heating by radio-loud AGNs has received much attention recently and may be an important process (Croton et al. 2006; Brüggen et al. 2007; Best 2007; Bower et al. 2006) for limiting cooling flows and the continued stellar growth of massive galaxies. However, another heating source which may be important, especially in radio-quiet galaxies, is gravitational interactions (Sparks 2004; Dekel & Birnboim 2008). Correlations between Hα emission and merger tracers such as dust and tidal tails provide suggestive evidence for a connection between gravitational interactions and the warm ionized gas in some ellipticals (Sparks 2004), but clear evidence for such connections has been limited. In this Letter we present compelling new evidence for a gravitational interaction origin for the Hα emission around the nearby elliptical M86.

The giant elliptical M86, near the core of the Virgo Cluster, is the most massive galaxy in a large group or subcluster now merging with the rest of the Virgo Cluster (Schindler et al. 1999). It is blueshifted by 1350 km s^{-1} with respect to M87 at the heart of the cluster, and thought to be falling into the Virgo Cluster from behind. We adopt a distance to M86 of 17.5 Mpc (Jacoby et al. 1990; Morris & Shanks 1998; Mei et al. 2007), which is ∼1 Mpc farther than the distance to M87. M86 has an unusually complex ISM. There is a bright "plume" of X-ray emission from hot gas, beginning $3' = 15$ kpc projected north of the nucleus and extending at least $10' = 50$ kpc projected to the NW (Forman et al. 1979). Several authors have suggested that this is a tail of gas stripped from M86 as it falls into the Virgo ICM (Forman et al. 1979; White et al. 1991; Rangarajan et al. 1995; Randall et al. 2008), although other X-ray properties are not consistent with a simple stripping picture (Finoguenov et al. 2004). M86 also has unusual clouds of H i (Bregman & Roberts 1990; Li & van Gorkom 2001) and far-infrared (Stickel et al. 2003) emission, whose origin has not been understood. Based on X-ray and FIR properties, Finoguenov et al. (2004) and Stickel et al. (2003) suggested galaxy collisions may be involved, but could not identify clear evidence for any collision. M86 is a very weak radio source (Dressel & Condon 1978; Hummel 1980; Fabbiano et al. 1989); thus the ISM complexities are unlikely to be related to AGN activity, but are instead likely due to interactions in a group and cluster environment.

In this Letter we present a deep wide-field Hα+[N ii] image around M86 which shows a highly complex and disturbed ISM/ICM, including striking new evidence for a collision between M86 and the nearby heavily disturbed spiral NGC 4438. Both galaxies have been the subject of numerous individual studies, but this is the first evidence that has clearly linked them together. We propose that most of the peculiarities of the ISM in M86 and NGC 4438 are due to this high-velocity collision, and discuss the implications for understanding the role of gravitational interactions in the energetics and evolution of the ISM in ellipticals.

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2. OBSERVATIONS AND DATA REDUCTION

The M86 region was observed with the MOSAIC imager on the KPNO 4 m Mayall telescope, in order to search for warm gas which could reveal clues about interactions. Exposures were taken using three filters: the Harris *R* (k1004, $\lambda/\delta\lambda$ = 6514 Å/1511 Å) broadband filter and two Hα narrowband filters—rest frame (k1009, 6575/81) and redshifted (k1010, 6521/80). We imaged the system with three different pointing centers, and with two different Hα filters, in order to have spatial coverage out to the nearby galaxies NGC 4438, NGC 4388, and M84, and wavelength coverage corresponding to both low (-1280 to 2380 km s^{-1} FWHM) and high (780 to 4430 km s^{-1}) velocities. Total exposure times per field/velocity were 2000 s for the *R* band, and 7000–8000 s for Hα. Images were processed and mosaicked together in a standard way, except for additional flat-fielding corrections using masked image frames, and a pupil correction for the Hα images. The Hα image superposed on an SDSS *gri* image (Adelman-McCarthy et al. 2007) is shown in Figure 1 (Plate 1), the *R*-band image is shown in the top panel of Figure 2 (Plate 2), and the Hα image is shown in the middle and bottom panels.

We obtained spectroscopy at 24 selected positions near M86 with the SparsePak integral field unit (IFU) on the WIYN telescope. SparsePak (Bershady et al. 2004) is a 90-fiber array which loosely covers an 80″ × 80″ field of view, with 5″ diameter fibers. The fibers feed the Bench Spectrograph with a 860 line mm^{-1} grating, providing a spectral resolution of 1.6 Å = 80 km s^{-1} and coverage from 5923 to 6862 Å. Each of the positions was observed for 1–2 hr. While the emission lines are strong and clearly detected in regions close to the center of M86, the lines are weak in some of the outer positions, and for these we co-add the spectra from several adjacent fibers to measure the emission lines. We detect both the Hα and the 6583 [N II] lines in these outer clouds, but cite the velocity of the Hα line, since it is usually stronger. Representative velocities from the spectroscopy are indicated in Figure 2 (*bottom*). Full imaging and spectroscopy results will be presented in a later paper.

3. RESULTS

The Hα morphology of M86 is very complex, as shown in Figure 2 (*middle*). There are filamentary features with a range of morphologies, but very few small compact H II region–like knots (except near NGC 4438), and no obvious FUV sources (Gil de Paz et al. 2007), and therefore very little star formation. We identify four major regions where the morphological characteristics of the Hα features appear to be distinct.

1. *The inner 1′-2′ of M86.*—The strongest Hα emission originates in the central 1′–2′ of M86, where it forms an asymmetric complex extending 2′ to the south of the nucleus, but only 1′ to the north. The unusual Hα morphology in this region was previously shown by Trinchieri & de Serego Alighieri (1991). Some of the central Hα emission is located in the same region as an unusual off-nuclear cloud of H I emission (Li & van Gorkom 2001), which extends from the nucleus to 2′ south (see Fig. 2, *middle*). The southern edge of the H I cloud is spatially coincident with semicircular arc of Hα which defines the southern limit of the "eastern" Hα filaments (described in region 2) suggesting they are physically associated. This region shows a disturbed velocity field, with all velocities within 250 km s^{-1} of the central velocity of -240 km s^{-1}.

2. *Near NGC 4438.*—Unusual Hα filaments were previously detected in NGC 4438, extending westward as far as 2′ from the nucleus (Keel & Wehrle 1993; Kenney et al. 1995). However the new, deeper observations show Hα emission with a much larger extent to the west, including a loop of emission extending 5′ from NGC 4438, apparently connecting to the filaments located between the two galaxies. Only a small fraction of the total Hα luminosity of NGC 4438 is in the form of small discrete knots consistent with H II regions (Kenney et al. 1995). A *GALEX* UV study also shows that the total star formation rate in this disturbed spiral is modest (Boselli et al. 2005).

3. *Loop feature northwest of M86.*—Extending 2′–8′ (10–40 kpc projected) from M86 to the NW at PA = 315° is a remarkably well-defined figure 8-shaped Hα loop. It has a roughly radial alignment, with total extent of 6′ in the radial direction, but only 1′–2′ in the tangential direction. This feature includes a linear filament 5′ = 22 kpc projected in length, and only 0.1′ in width implying an aspect ratio of 50 : 1, which suggests a minimum of turbulence in this part of M86's ISM. This Hα loop is spatially coincident with the bright NW X-ray plume (Fig. 2, *middle*) and an associated H I cloud, suggesting that they are all related. Unlike the eastern filaments, this feature is blueshifted with respect to M86, with velocities of -230 to -450 km s^{-1}.

4. *Features extending eastward from M86 toward NGC 4438.*—There are a remarkable series of features east of the M86 nucleus, which clearly extend to the large disturbed spiral galaxy NGC 4438 located 23′ = 120 kpc projected away. These features reach to within 1′–2′ of the M86 nucleus, and are centered about a well-defined axis with a PA = 82° ± 1° which passes through the centers of both galaxies. There are several distinct features between the two galaxies, including a roughly triangular feature 1′–5′ east of the M86 nucleus, and a curved arc of emission roughly halfway between the galaxies. There is a large range in velocities in the triangle feature close to (1′–2′ east of) M86, but otherwise there is a fairly smooth velocity gradient between M86 and NGC 4438, with -240 km s^{-1} for M86, -150 km s^{-1} for the arc between the two galaxies, -40 km s^{-1} for a cloud between the arc and NGC 4438, and $+70$ km s^{-1} for NGC 4438. The continuity of the kinematics and morphology imply a physical association between M86 and NGC 4438.

The total Hα+[N II] luminosity of the M86–NGC 4438 complex is 1.3×10^{41} erg s^{-1}. Of this total, 32% arises within 2′ of M86, 50% within 5′ of N4438, 12% between the two galaxies, and 5% from the NW figure 8 loop. The Hα+[N II] luminosity of M86 is in the top 20% of nearby bright ellipticals and S0's (Macchetto et al. 1996), and is the second largest among Virgo ellipticals with a luminosity ~2.5 times lower than M87 in the center of the cluster.

4. DISCUSSION

We propose that most of the Hα features mark a gaseous debris trail and wake caused by the passage of NGC 4438 through the ISM of M86. This would make the M86–NGC 4438 system the nearest example of a recent high-velocity collision between a large elliptical and large spiral.

NGC 4438 (Arp 120) is the most heavily disturbed large spiral in the Virgo Cluster. The outer stellar disk is disturbed, forming extraplanar tidal arms, indicating a strong gravitational interaction. The ISM of NGC 4438 is even more disturbed than the stars. In particular, all ISM tracers in NGC 4438 are displaced to the west of the stellar disk (Kenney et al. 1995), on the side toward M86, where they appear to connect to the large-scale Hα filaments linking NGC 4438 to M86. NGC 4438 is very H I–deficient, with an H I mass of $4 \times 10^8 M_\odot$, only ~5%–15% of the expected H I mass for a spiral galaxy of its size (Giovanardi et al. 1983; Kenney et al. 1995; Solanes et al. 2002; Gavazzi et al. 2005). This suggests that $(5 \pm 2) \times 10^9 M_\odot$ of gas has recently been lost from NGC 4438, or converted into other forms. While some ram pressure stripping may also be expected from NGC 4438's passage through the general Virgo ICM (Vollmer et al. 2005), the results in this Letter (further developed below) suggest that most of the ISM of NGC 4438 was stripped from its stellar disk by the ram pressure caused by its passage through M86's ISM. Previous papers (Combes et al. 1988; Kenney et al. 1995; Vollmer et al. 2005) have suggested that the enormous disturbances to NGC 4438 are due to a collision with the SB0 galaxy NGC 4435, which lies very nearby (only 5′ away) on the sky. However NGC 4435 shows no clear signs of disturbance itself. Its stellar distribution and its small nuclear gas and dust disk appear normal. With a radial velocity 700 km s^{-1} higher than that of NGC 4438, NGC 4435 is probably unrelated to the disturbances of NGC 4438. The Hα imaging and kinematics presented in this Letter, showing a clear connection between M86 and NGC 4438, provides strong evidence that most of the disturbances to NGC 4438 were caused by a collision with M86. For an average plane-of-sky velocity of 800 km s^{-1} (less than peak velocity) the time since closest approach in the collision would be 100 Myr, a timescale consistent with the stellar populations in the outer disk of NGC 4438 (Boselli et al. 2005).

Cool gas stripped from NGC 4438 is a reasonable explanation for the unusual clouds of H I near M86 (Li & van Gorkom 2001). Figure 2 (*middle*) shows that the two of the largest H I clouds in M86 lie within the eastern Hα filament system that connects the two galaxies, suggesting that they originated from NGC 4438, and were stripped from it during the collision. Indeed, the lower edge of the southern H I cloud is spatially coincident with the lower Hα filaments which connect M86 and NGC 4438. A third H I cloud is associated with the NW X-ray plume (Li & van Gorkom 2001). The total H I mass in M86 of $2 \times 10^8 M_\odot$ (Bregman & Roberts 1990) is a small fraction of the H I missing from NGC 4438, and the remainder may have been heated and entered another phase within the halo of M86. The mass of Hα-emitting gas in uncertain, as it depends on the poorly known gas densities, but small, probably less than $10^7 M_\odot$ (Macchetto et al. 1996).

While it is pretty clear that the eastern filaments connecting M86 and NGC 4438 are caused by the collision, it is less clear whether the NW Hα loop and associated X-ray ridge are due to the collision. Previous authors have suggested that this prominent high-surface-brightness X-ray ridge in the NW is a tail of gas stripped from M86 as it falls into the Virgo ICM (Forman et al. 1979; White et al. 1991; Rangarajan et al. 1995; Randall et al. 2008). However, the X-ray morphology of M86 is unlike those in other Virgo and Fornax E galaxies with evidence for ram pressure stripping, which show sharp, flattened leading surface brightness edges consistent with bow shocks and centered trailing tails (Machacek et al. 2005, 2006). There are a number of observations in M86 which are not consistent with a simple stripping picture, and more easily understood in a collision scenario: the presence of an extended X-ray halo which appears mostly relaxed, unlike the complexities in the core (Finoguenov et al. 2004), and the presence of discrete clouds of H I and FIR emission at various locations within the halo, including within the NW ridge. The NW gas ridge may be a ram pressure stripped gas tail disturbed by the collision. Alternately, we propose that the NW X-ray ridge, Hα loop, and H I cloud are related to the incoming part of NGC 4438's trajectory through the M86 halo, during which most of NGC 4438's cool gas was stripped and subsequently heated. The blueshift of this gas relative to M86, which is opposite that the eastern filaments, is consistent with the following collision scenario: NGC 4438 approaches M86 from behind and as it accelerates toward M86, it is blueshifted. Gas in a ram pressure stripped tail should be accelerated toward the cluster mean velocity, and therefore redshifted, opposite from what is observed.[5]

Cool gas stripped from NGC 4438 and deposited in its wake will be moving within the hot gaseous halo of M86, and subject to heating. The source of excitation of the warm ionized gas is unlikely to be UV photoionization from stars, since there are no FUV sources detected from *GALEX* (Gil de Paz et al. 2007) and the Hα image shows very few compact H II regions. The spatial correlation of H I, Hα, and X-ray emission in M86 (Fig. 2, *middle*) is suggestive of warm ionized gas at the interface between cold and hot gas, and suggests that the excitation of the Hα filaments is due to shocks, collisional excitation from ram pressure drag (Dekel & Birnboim 2008), or thermal conduction from the hot halo (Sparks 2004; Conselice et al. 2001).

The kinetic energy of the gas stripped from NGC 4438 in the collision is likely a significant heating source for the ISM of M86. The ratio of X-ray to optical luminosity in M86 is significantly higher than the average value for ellipticals (Diehl & Statler 2007), perhaps a consequence of heating in the collision. In order for NGC 4438 to pass close to the center of M86, and escape as far away as 120 kpc projected with a relative velocity of more than 300 km s^{-1}, it must have been moving much faster, exceeding the escape speed, which is ~1000 km s^{-1} at $R = 10$ kpc, when it passed through the center. Assuming $5 \times 10^9 M_\odot$ of gas stripped from NGC 4438 during its passage through M86's gaseous halo, and a relative velocity at closest approach of 1000 km s^{-1}, the kinetic energy of the stripped ISM is 5×10^{58} erg, a significant fraction of which will be absorbed by the ISM of M86 in the collision. This is similar to the thermal energy $nkTV$, of M86's ISM, $\sim 10^{59}$ erg, where we have assumed $kT = 1.0$ keV, an average density of $n = 2 \times 10^{-3}$ cm^{-3} over the volume V of a sphere with radius of 15′ = 73 kpc projected, roughly the area of the *ROSAT* X-ray emission (Rangarajan et al. 1995; Randall et al. 2008). Thus the collision will be a significant energy source for M86's ISM, and might act to prevent the gas from cooling to form stars. While there has been significant attention paid recently to the heating effects of AGN in early-type galaxies (Croton et al. 2006; Brüggen et al. 2007), gravitational heating through collisions, mergers, and gas accretion can be a significant heating source (Dekel & Birnboim 2008). While M86 is certainly an extreme case, the effects are easier to study in extreme cases,

[5] There is also the possibility of another collision, between M86 and a third galaxy, the spiral NGC 4388, which lies 10′ south of M86. A long tail of H I gas stripped from NGC 4388 extends up toward M86 (Oosterloo & van Gorkom 2005). However, the line-of-sight velocity of NGC 4388 and its H I tail range from 2100 to 2500 km s^{-1}, much higher than M86, NGC 4438, and the Hα emitting gas. We have detected the high-velocity extended emission (shown in green in Fig. 1) previously detected within 5′ of NGC 4388 (Yoshida et al. 2004), but no high-velocity Hα emission coincident with the northern parts of the H I tail close to M86. This suggests that the H I tail of gas stripped from NGC 4388 may be unrelated to M86, although this possibility warrants further investigation.

and thus this system will have implications for understanding the ISM and ICM heating which occurs in the hierarchical assembly of galaxies and clusters.

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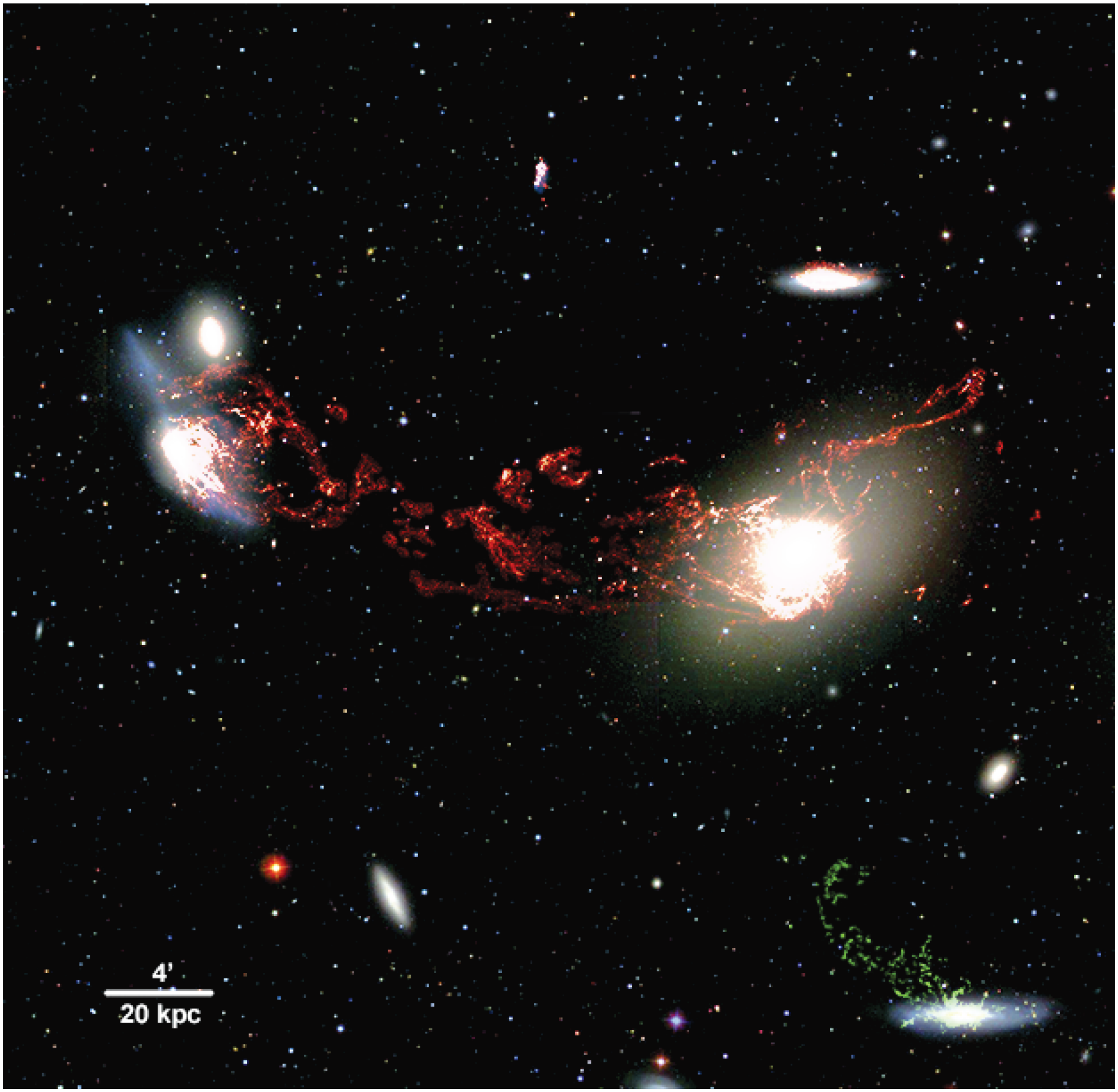

PLATE 1

FIG. 1.—Hα+[N II] image of M86 region superposed on a color SDSS *gri* image. The Hα image is stretched to highlight the faint emission. The “low-velocity” (<500 km s^{-1}) Hα+[N II] emission is colored red, and the “high-velocity” (>2000 km s^{-1}) Hα+[N II] emission is colored green. The low-velocity emission is attributed to gas stripped from NGC 4438 in a collision with M86 and subsequently heated. High-velocity emission is observed near NGC 4388 in the lower right, although it does not extend all the way to M86, so it is unclear whether it is related.

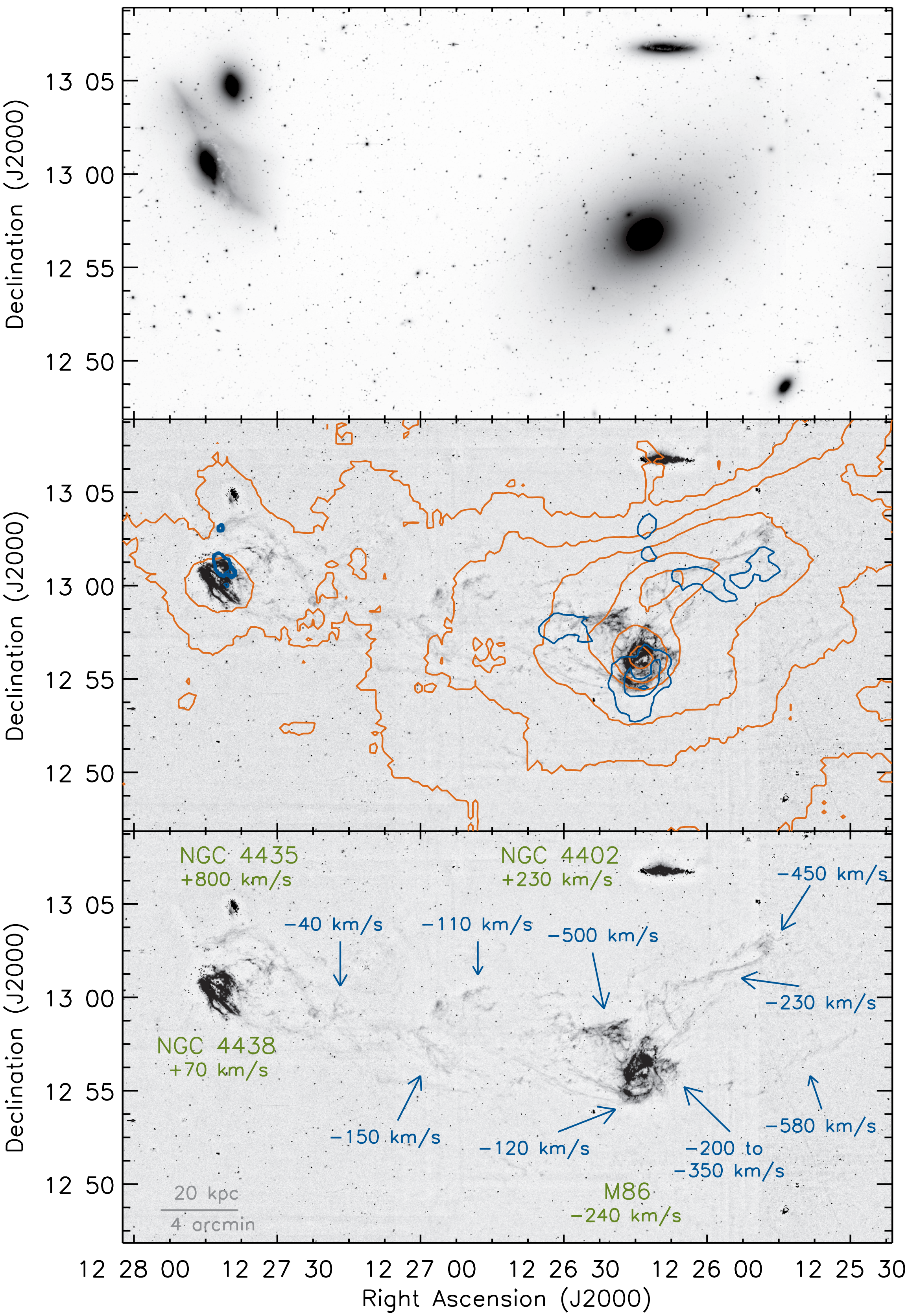

PLATE 2

FIG. 2.—*Top*: *R*-band image of M86 and NGC 4438 region, shown with logarithmic stretch. *Middle*: Hα+[N II] image of M86 and NGC 4438 region, shown with a logarithmic stretch to highlight the fainter features. *ROSAT* X-ray contours (*red*) and VLA H I contours (*blue*) are superposed. Hα, H I, and X-ray peaks are closely associated in several regions. NGC 4438 has both X-ray and H I emission offset toward the west, associated with some of the Hα filaments. *Bottom*: Hα+[N II] image of M86 and NGC 4438 region, with Hα velocities of selected features identified.