

The filament of ionized gas in the outskirts of M87*

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Abstract. We report on the filament of ionized gas found at the NE periphery of M87, the second brightest elliptical galaxy in the Virgo cluster. The object lies at 3.16 arcmin (15.7 kpc) projected distance of the nucleus of M87, and it coincides in position with the Eastern radio lobe of M87. Long slit spectroscopy confirmed the gaseous nature of this object, showing H_{β} , [OIII], [OI], [NII], H_{α} and [SII] lines, without any underlying continuum. The redshift of the object, $V = 1170 \pm 25 \text{ km s}^{-1}$, agrees with the velocity of M87 itself ($V = 1280 \text{ km s}^{-1}$), and with the bulk of the ionized material found near the center of M87. The H_{α} flux of this filament corresponds to 1% of the ionized material in M87. The radio-optical coincidence together with the spectral characteristics suggest that the filament is ionized by a shock.

Key words: galaxies: individual: M87 – galaxies: interactions – galaxies: ISM

1. Introduction

The filamentary H_{α} structure associated with M87 on a scale of approximately 2 arcmin, discovered by Arp (1967), was studied by Ford & Butcher (1979) and more recently by Sparks et al. (1993). The morphology and kinematics of the ionized gas led these authors to consider, among other possibilities, a scenario where a gas-rich galaxy is being cannibalized by M87. High resolution HST observations of the inner 1 arcmin were consistent with this picture and provided evidence that the infalling material is feeding the central black hole in M87 (Harms et al. 1994; Ford et al. 1994). We serendipitously included M87 in a narrow band image of the center of the Virgo cluster aimed at studying the H_{α} emission from VCC1313, a dwarf galaxy near M87. We used a camera with a field of view of 34×34 arcmin which allowed us to include the lump of ionized material at the NE periphery of M87, which was reported by Baum et al. (1988) to coincide in position with the Eastern radio-lobe of M87. Baum

& Heckman (1989) discussed the statistical properties of the line-emission associated with powerful radio galaxies and concluded that the mechanisms responsible for the ionization in these objects is either photoionization by UV photons of nuclear origin, or ionization by shocks. To confirm kinematically the connection of the outer filament with M87, and to constrain observationally its ionization properties we took a low dispersion spectrum of the filament. The present paper reports on these findings.

2. Observations

We took observations of M87 through a narrow band filter centered at 6568 Å (95 Å bandpass). The image was obtained in the photometric night of Feb 21, 1999, in 1.2 arcsec seeing conditions, with the Wide Field Camera at the prime focus of the Isaac Newton Telescope (INT) at La Palma. The camera relies on 4 Chip Mosaic of thinned AR coated EEV 4K \times 2K CCDs, with pixels of $13.5 \mu\text{m} \times 13.5 \mu\text{m}$ (0.33 arcsec \times 0.33 arcsec), giving a field of view of 34×34 arcmin. The ON-band filter was selected to cover the redshifted H_{α} and [NII] lines. The underlying continuum was taken through the Johnson R filter. The integration time was 4500 sec (ON-band), split in three shorter exposures to get rid of the cosmic rays, each dithered by 18 arcsec to recover the gap between the 4 chips. The red-continuum frame was exposed 100 sec to avoid saturation on the nucleus of M87. The photometric calibration was obtained exposing the spectrophotometric star Feige 56 on each of the 4 CCD chips.

We obtained low dispersion spectra of the object with the 1.93 m telescope of the Observatoire de Haute Provence (OHP), equipped with the Carelec spectrograph (Lemaitre et al. 1990) coupled with a 2K \times 1K EEV CCD, giving a spatial scale of 0.6 arcsec per pixel. The observations were carried out in the night of February 3, 2000 in approximately 2 arcsec seeing conditions through a slit of 5 arcmin \times 2.5 arcsec. The selected grism gives a spectral resolution of 900 (133 Å/mm or 1.79 Å/pix) and a spectral coverage in the region 3200–7100 Å, containing the redshifted H_{β} (λ 4861.3 Å), [OIII] (λ 5006.8 Å), H_{α} (λ 6562.8 Å), the [NII] doublet ($\lambda\lambda$ 6548.1, 6583.4 Å) and the [SII] doublet ($\lambda\lambda$ 6717.0, 6731.3 Å). To ensure having most light from the target object (invisible on the TV camera) in the slit we took spectra along two P.A. (29 and 314 degrees), with

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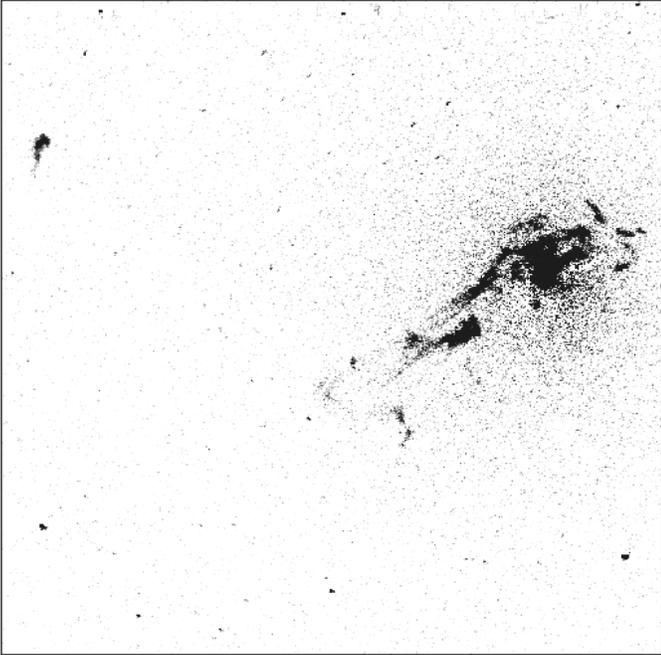


Fig. 1. The filamentary structure of M87 is visible to the right of this H_α NET image (4×4 arcmin field). The filament is visible at the upper left. North is up, East to the left.

the slit aligned with some reference stars. The object was exposed 60 minutes and a final spectrum was extracted over the wavelength range $\lambda \lambda 4000\text{--}7000 \text{ \AA}$. The calibration was obtained on the spectrophotometric star Feige 34. Both images and spectrum were reduced using standard procedures within the IRAF environment.

3. Results

Fig. 1 gives the the continuum subtracted (NET) image of M87, showing the filamentary H_α structure of M87. We obtain a total $H_\alpha + [\text{NII}]$ flux of $1.18 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$, in very good agreement with Sparks et al. (1993) At the NE periphery of M87 ($R.A. = 12^h 31^m 02.14^s$; $Dec = 12^\circ 24' 11.0''$; J2000) we detect the presently discussed filament of H_α emission (the astrometry was performed relative to two stars in HST Guide Star Catalogue within 2 arcmin from the filament). This corresponds to 3.16 arcmin (15.7 kpc) projected distance from the nucleus of M87 (assuming a distance to M87 of 17 Mpc), thus the object lies inside the stellar envelope of M87 whose isophotal radius at the 25^{th} mag arcsec^{-2} level is 4.2 arcmin.

Fig. 2 gives enlargements of the region containing the object, which is clearly detected in the ON-band image (Fig. 2a), while the total absence of extended underlying continuum is evidenced by the lack of detection in the red-continuum frame (Fig. 2b). The central faint star is at $R.A. = 12^h 31^m 02.14^s$; $Dec = 12^\circ 24' 11.0''$; J2000 ($R.A. = 12^h 28^m 30.34^s$; $Dec = 12^\circ 40' 45''$; B1950). The object has a bright northern feature extending 6 arcsec to the N of this position, along with a faint southern tail (with 14 arcsec extension). The maximum extension is thus 20 arcsec N-S, and

Table 1. The line parameters

(1)	(2)	(3)	(4)
	λ	V	$flux$
H_β	4879.65	1131	0.26
[OIII]	5028.24	1285	0.22
[OI]	6324.20	1152	0.18
[NII]	6574.10	1191	0.45
H_α	6588.70	1184	1
[NII]	6609.56	1192	0.90
[SII]	6743.03	1163	0.34
[SII]	6557.56	1170	0.19

8 arcsec in the E-W direction. Altogether the filament has a “bow shape” appearance. The $H_\alpha + [\text{NII}]$ flux from the object is $10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$, corresponding to approximately 1% of the ionized material in M87.

We checked the positional correspondence between the filament and the “large-scale” radio source associated with M87. This is given in Fig. 3, where the 327 MHz radio map kindly provided by F. Owen (with 5 arcsec resolution) is overlaid on top of our H_α net image. The filament is found within the eastern radio lobe of M87, in contrast with Baum et al. (1988) who position the filament on the eastern-edge of the radio lobe, at approximately $R.A. = 12^h 28^m 32.5^s$ (B1950), i.e. 30 arcsec to the E of our position (see their Fig. 35). The exact location of the filament is inside the northern “arc” which constitutes the radio lobe, near to its N-W edge, about 30 arcsec to the north of the tip of the radio beam.

The red part of the spectrum of the filament is shown in Fig. 4. We detect strong [NII] doublet bracketing the H_α line, the [SII] doublet and weak [OI]. More in the blue we detect weak H_β and [OIII]. No trace of continuum is present in the spectrum. The line parameters are listed in Table 1. For each line (Column 1) the observed wavelength (\AA) is given in Column 2, followed by the observed recessional velocity (not corrected to heliocentric) in Column 3, and by the intensity relative to H_α (Column 4) (unexpectedly the ratio [NII] $\lambda 6548$ / [NII] $\lambda 6583$ differs from the canonical 0.3). The average redshift of the object (excluding the discrepant [OIII]) is $V = 1170 \pm 25 \text{ km s}^{-1}$. No significant line broadening is detected, as the line widths of [NII], H_α and [SII] are found consistent with 6.2 \AA i.e. with the width of the sky lines.

4. Discussion

The most plausible interpretation of the observations presented in this paper is that the filament of ionized material found in the outskirts of M87 is associated with the ionized gas found near the nucleus of M87. In fact its redshift corresponds within 100 km s^{-1} to that of M87 and of the filamentary ionized gas. Based on the estimate of Sparks et al. (1993) the ionized gas associated with M87 amounts to only $10^{5-7} M_\odot$, thus the filament itself must contain a tiny fraction of gas $\sim 10^{3-5} M_\odot$. The plasma density derived from the $[\text{SII}]\lambda 6716 / [\text{SII}]\lambda 6731$

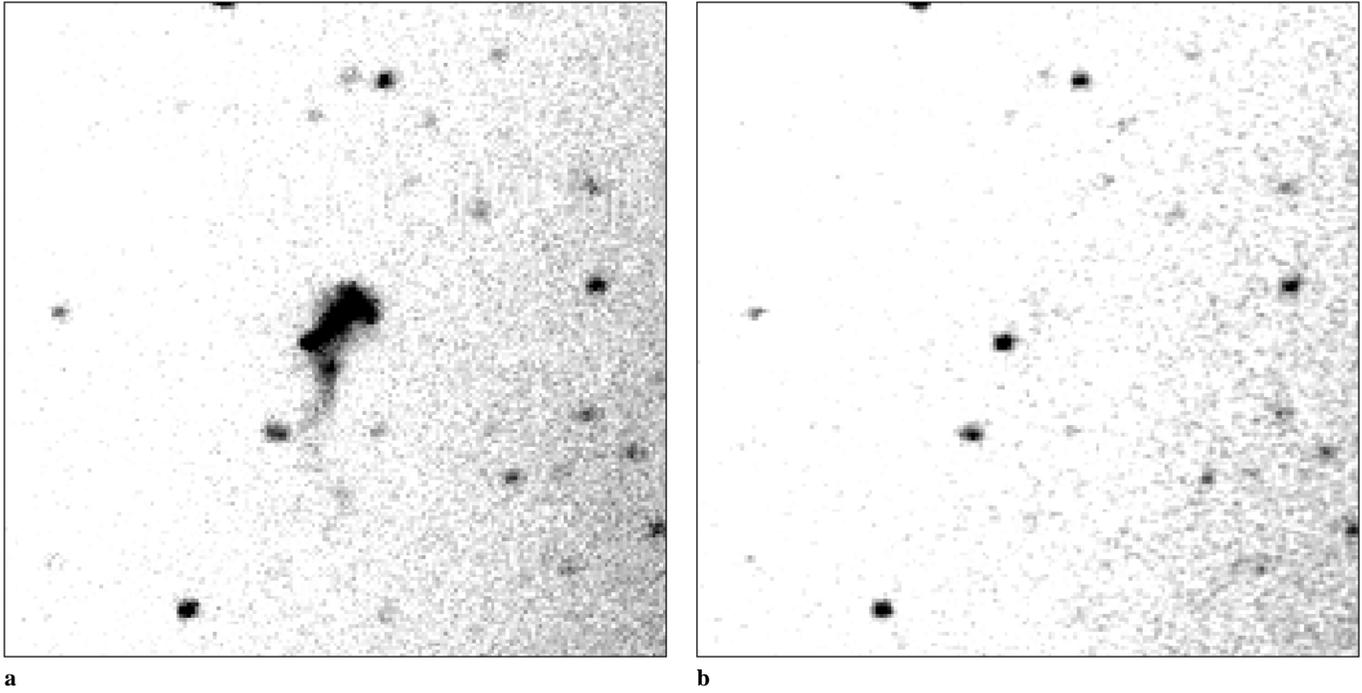


Fig. 2a and b. Enlargements of the 1×1 arcmin region containing the filament in the $H\alpha$ ON-band **a** and in the red-continuum **b** frames. North is up, East to the left.

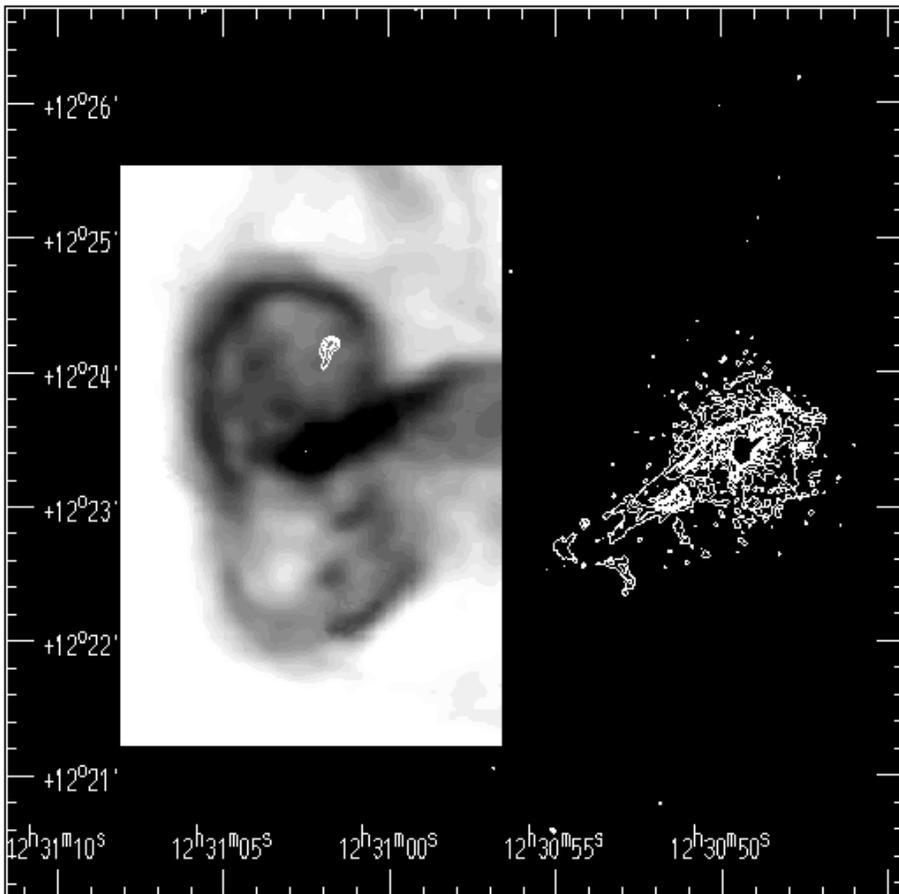


Fig. 3. The $H\alpha$ net image (arbitrary contours) superposed onto the East radio lobe of M87 (grey-scale, adapted from the 327 MHz map kindly provided by F. Owen). J2000 celestial coordinates are given.

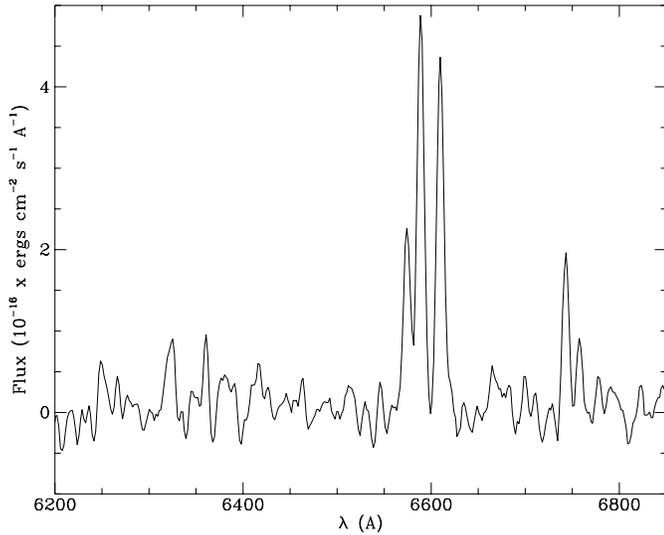


Fig. 4. The red part of the spectrum of the filament containing [OI], [NII], H_{α} and [SII].

ratio is near to the low density limit of 10 cm^{-3} , i.e. one or two orders of magnitude below ordinary HII regions (Osterbrock, 1989). Besides the irrelevant mass and plasma density of the filament, its strong [NII] intensity as well as the fluxes of [OI] and [SII] relative to H_{α} , together with the [OIII] to H_{β} ratio are not typical of HII regions, nor of Seyfert galaxies, but coincide with the zone of LINERS in diagnostic diagrams (e.g. Veilleux & Osterbrock 1987). Moreover the intensity ratios observed in the filament differ markedly from those found in the central part of M87 and in other cooling-flow systems by Heckman et al. (1989). The $[NII]\lambda 6584/H_{\alpha}$ and $[SII]/H_{\alpha}$ are a factor of two lower than in the center of M87, indicating a lower degree of ionization. Because of the irregular filamentary morphology of the source and the lack of extended underlying continuum, photoionization by stellar sources – hot young stars (Kim 1989), post-AGB stars (Binette et al. 1994) – seems ruled out. Similarly ionization by UV photons originated in the active nucleus of M87 seems unlikely because the filament is far from the nucleus. Other mechanisms cannot be ruled out, such as for example X-ray heating by the ICM (Donahue & Voit 1991), as suggested by the correspondence with the X-ray elongation found by Harris et al. (2000). This class of models successfully explains the high H_{α}/H_{β} and $[NII]/H_{\alpha}$ ratios as well as the H_{α}

surface brightness of the filament and was invoked by Heckman et al. (1989) and by Sparks et al. (1989) as the likely explanation for the presence of ionized gas in cooling flow systems. The ionization mechanism which provides the best consistency with the line diagnostics of the filament is by intermediate velocity shocks (Dopita & Sutherland 1995). This is consistent with the positional correspondence found with the Eastern radio-lobe of M87, which strongly argues in favour of the presence of shocks. It is unclear, however, why the filament is confined to a small volume within the larger shocked region and does not coincide exactly with any of the shock surfaces, nor with the tip of the radio beam, as would be expected if the gas was isotropically supplied by the IGM. It probably indicates that the ionization occurs on a small lump of gas left over from the gas-rich galaxy which was swallowed by M87.

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