The gamma-ray monitoring of newly discovered Be/BH binary system MWC 656

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• The AGILE satellite
• The Fermi satellite
• Motivation
• Counterparts
  • MWC 656
  • RX J2243.1+4441
• Follow-up
  • AGILE data analysis
  • Fermi data analysis
  • Comparison AGILE vs Fermi
• Conclusions
THE AGILE SATELLITE

• AGILE (Astrorivelatore Gamma a Immagini LEggero)

• Two main instruments:
  • Super Agile: hard X-ray detector
  • GRID: gamma-ray camera
    • Energy range: 50 MeV - 50 GeV
    • PSF: 4°@100MeV - 0.8°@ 1GeV

• Operation modes:
  • Pointing, from launch until october 2009
  • Spinning, from october 2009 on
THE FERMI SATELLITE

- Two instruments
  - GBM
  - The LAT (Large Area Telescope)
    - Energy range: 30 MeV - 300 GeV
    - PSF: 2°@300MeV - 0.8°@ 1GeV

- Operation mode:
  - Scanning: covering most of the sky every few hours
THE AGILE SATELLITE

Full band (E>100 MeV) AGILE all-sky map (pointing + spinning up to 2012)
THE FERMI SATELLITE

Fermi/LAT (E > 1 GeV) all-sky map after 5 years of observation
In July 2010 AGILE detected transient gamma-ray source AGL J2241+4454 (Lucarelli et al. 2010) at galactic coordinates (l, b) = (100°.0, -12°.0) ± 0.°6

- Significance > 5σ, Flux(E>100MeV)=1.5×10^{-6} ph cm^{-2} s^{-1}
MOTIVATION

\[ (\ell, b) = (100.29, -12.27) \pm 0.65 \]

Sabatini et al. (2016) in preparation
POSSIBLE COUNTERPARTS: RX J2243.1+4441

- Observed with XMM-Newton (15 ks) and VLA
- Detected at more than 5$\sigma$ in both
- Difficult to obtain X-ray spectrum because it is at the border of the ccd
- Radio core flux 2.2 mJy/beam
  - South lobe seems variable (galactic source overlapped?)
- Morphology similar to FR-II
  - less probability of gamma-ray emission?

VLA 3GHz + XMM 0.2-10 keV contours

Adapted from Marcote 2015, PhD Thesis
POSSIBLE COUNTERPARTS: MWC 656

- Discovered thanks to the AGILE detection of a gamma-ray flare (Lucarelli et al. 2010)
- Williams et al. (2010) found photometric eriodicity. Binary system?
- Confirmed as a binary system by Casares et al. (2012)
- Be star orbited by a BH (Casares et al. 2014) with a mass between 3.8 and 6.9 M☉
- MWC 656 is the first known binary system of this class
- Confirmed as a HMXB by Munar-Adrover et al. (2014)

Table 1 | Orbital elements for MWC 656

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{orb}}$ (days)</td>
<td>60.37 (fixed)</td>
</tr>
<tr>
<td>$T_0$ (HJD – 2,450,000)</td>
<td>3,243.70 ± 4.30</td>
</tr>
<tr>
<td>$e$</td>
<td>0.10 ± 0.04</td>
</tr>
<tr>
<td>$\omega$ (degrees)</td>
<td>163.0 ± 25.6</td>
</tr>
<tr>
<td>$\gamma$ (km s$^{-1}$)</td>
<td>–14.1 ± 2.1</td>
</tr>
<tr>
<td>$K_1$ (km s$^{-1}$)</td>
<td>32.0 ± 5.3</td>
</tr>
<tr>
<td>$K_2$ (km s$^{-1}$)</td>
<td>78.1 ± 3.2</td>
</tr>
<tr>
<td>$a_1 \sin i$ ($R_\odot$)</td>
<td>38.0 ± 6.3</td>
</tr>
<tr>
<td>$a_2 \sin i$ ($R_\odot$)</td>
<td>92.8 ± 3.8</td>
</tr>
<tr>
<td>$M_1 \sin^3 i$ ($M_\odot$)</td>
<td>5.83 ± 0.70</td>
</tr>
<tr>
<td>$M_2 \sin^3 i$ ($M_\odot$)</td>
<td>2.39 ± 0.48</td>
</tr>
<tr>
<td>$M_2/M_1$</td>
<td>0.41 ± 0.07</td>
</tr>
<tr>
<td>$\sigma_1$ (km s$^{-1}$)</td>
<td>16.7</td>
</tr>
</tbody>
</table>

Casares et al. (2014)

Image credit: Gabriel Pérez - SMM (IAC)
POSSIBLE COUNTERPARTS: MWC 656

Be star

Interesting because it is the first known case of a binary system containing a Be star and a BH

Accretion-ejection coupling in XRBs

Image credit: Sera Markoff

Image credit: Gabriel Pérez - SMM (IAC)
• Observed with *XMM-Newton* (15 ks)

• We detect a faint source at 4σ c.l. coincident with the position of MWC 656

• X-ray source position compatible with the *Hipparcos* position of MWC 656 at 2.4σ

• Detected only in the 0.3-5.5 keV range

• Spectrum with low number of counts (0.3-5.5 keV energy range)

POSSIBLE COUNTERPARTS: MWC 656

Munar-Adrover et al. (2014)
POSSIBLE COUNTERPARTS: MWC 656

- Radio observations with VLA (Dzib et al. 2015): 7 dedicated obs. in 2015
- Detection of a source compatible with the position of MWC 656
- Variable radio flux in week scales
  - 2h obs @ 8-12 GHz: $14.2 \pm 2.9 \mu Jy$ (epoch 1, orbital phase 0.49)
  - integration of 6 obs @ 8-12 GHz: $3.7 \pm 1.4 \mu Jy$ (epoch 2-7)

![Images showing detection of a radio source compatible with the position of MWC 656.](image-url)
POSSIBLE COUNTERPARTS: MWC 656

Munar-Adrover et al. (2014)

MWC 656 HMXB

Cyg X-1 HMXB

LMXB correlation

quiescence

Munar-Adrover et al. (2014)
GAMMA-RAY FOLLOW-UP OBSERVATIONS

• **Analysis strategy** *(AGILE and Fermi/LAT)*:
  
  • Blind search in 2-days bins
  
  • Search for **periodicity**
  
  • Search for **steady emission**
  
  • Stack detected events to get a **spectrum**
• Blind search: 10 flaring events registered by AGILE between 2007 and 2013

**AGILE gamma-ray transient detections around the position of MWC 656.**

<table>
<thead>
<tr>
<th>$l$</th>
<th>$b$</th>
<th>$t_{start}$</th>
<th>$t_{end}$</th>
<th>Flux</th>
<th>$\sqrt{TS}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[°]</td>
<td>[°]</td>
<td>[UT]</td>
<td>[UT]</td>
<td>[$\times 10^{-6}$ cm$^{-2}$ s$^{-1}$]</td>
<td></td>
</tr>
<tr>
<td>100.28</td>
<td>-13.22</td>
<td>2007-11-23 UT00:02:10</td>
<td>2007-11-24 UT12:02:12</td>
<td>1.5 ± 0.5</td>
<td>4.5</td>
</tr>
<tr>
<td>100.22</td>
<td>-12.61</td>
<td>2008-06-28 UT12:03:15</td>
<td>2008-06-30 UT06:03:15</td>
<td>0.6 ± 0.3</td>
<td>3.2</td>
</tr>
<tr>
<td>101.74</td>
<td>-11.25</td>
<td>2009-01-04 UT12:02:12</td>
<td>2009-01-07 UT00:02:12</td>
<td>0.5 ± 0.2</td>
<td>3.1</td>
</tr>
<tr>
<td>100.94</td>
<td>-12.65</td>
<td>2010-06-13 UT12:01:06</td>
<td>2010-06-14 UT18:01:06</td>
<td>1.4 ± 1.1</td>
<td>3.2</td>
</tr>
<tr>
<td>99.27</td>
<td>-11.50</td>
<td>2010-06-30 UT00:01:06</td>
<td>2010-07-02 UT00:01:06</td>
<td>1.3 ± 0.6</td>
<td>3.1</td>
</tr>
<tr>
<td>99.96</td>
<td>-12.24</td>
<td>2010-07-25 UT00:02:12</td>
<td>2010-07-27 UT00:02:12</td>
<td>1.4 ± 0.6</td>
<td>3.8</td>
</tr>
<tr>
<td>99.94</td>
<td>-12.76</td>
<td>2011-10-08 UT00:02:12</td>
<td>2011-10-10 UT00:02:12</td>
<td>2.5 ± 1.1</td>
<td>3.4</td>
</tr>
<tr>
<td>101.70</td>
<td>-12.51</td>
<td>2011-04-09 UT00:02:12</td>
<td>2011-04-11 UT00:02:12</td>
<td>2.2 ± 1.1</td>
<td>3.1</td>
</tr>
<tr>
<td>100.38</td>
<td>-12.70</td>
<td>2013-07-10 UT00:00:00</td>
<td>2013-07-12 UT00:00:00</td>
<td>3.2 ± 1.6</td>
<td>3.5</td>
</tr>
<tr>
<td>100.34</td>
<td>-11.81</td>
<td>2013-03-07 UT00:00:00</td>
<td>2013-03-08 UT09:00:00</td>
<td>2.6 ± 1.4</td>
<td>3.1</td>
</tr>
</tbody>
</table>

from Le Hoang master thesis (2014)
AGILE DATA ANALYSIS

Ephemeris from Casares et al. (2014)

$\phi_{sc} = 0.28$

$\phi_{ic} = 0.84$

To observer

$\phi = 0$

AGILE detections

AGILE, Atel 2761

Sabatini et al. (2016) in preparation
Sabatini et al. (2016) in preparation
AGILE DATA ANALYSIS

- **AGILE spectrum** between 100 MeV and 3 GeV
- Integrating over all detected gamma-ray flares
- Spectral fit with photon index $\Gamma = 2.3 \pm 0.2$

Sabatini et al. (2016) in preparation
**FERMI/LAT DATA ANALYSIS**

- Pass 8 data
- Blind search in 2-day bins: no significant events
- Steady emission: UL for 6 years integration: $2.2 \times 10^{-10}$ cm$^{-2}$ s$^{-1}$
- Stacking of AGILE detected flares: UL integrating all flares: $3.0 \times 10^{-8}$ cm$^{-2}$ s$^{-1}$
- Search for periodic emission

Sabatini et al. (2016) in preparation
• *Fermi* and *AGILE* effective area decrease with zenith distance (ZD), specially above 50°

• We checked the source ZD at any given moment for the entire *Fermi* and *AGILE* missions

• During *AGILE* 2010 flare, *MWC 656* is almost always at ZD > 50° for *Fermi*
COMPARISON: AGILE vs FERMI

• Time spent by AGILE and Fermi/LAT observing MWC 656 at different ZD

• Flares:
  • AGILE: more than 50% of time at ZD < 50°
  • Fermi/LAT: only 20% of time at ZD < 50°

• Rest of time:
  • AGILE: on average 30% of time spent at ZD < 50°
  • Fermi/LAT: on average 12% of time spent at ZD < 50°

Sabatini et al. (2016) in preparation
CONCLUSIONS

• AGILE detection by *Lucarelli et al. (2010)* of AGL J2241+4454 triggered the study of this region of the sky

• The first Be/BH system was discovered

• *Munar-Adrover et al. (2014)* discovered the X-ray counterpart of MWC 656. It is a high-mass X-ray binary. Two spectral components: thermal and non thermal. System at the quiescent state with very low luminosity

• AGILE follow-up revealed 10 flares. Spectrum derived by stacking them. No sign of periodicity or recurrence

• *Fermi/LAT* does not detect the flares or any other episode of activity from MWC 656 field

• Reason of discrepancy might be differences in off-axis position of MWC 656 between AGILE and *Fermi/LAT* during the occurrence of the flares

• Future work: theoretical modelling (ADAF, etc.)
Thank you

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Back up
COMPARISON: AGILE vs FERMI

Sabatini et al. (2016) in preparation
FERMI BLIND SEARCH

2-day bins
FERMI FLARE PHOTON ARRIVAL TIME
WORK IN PROGRESS: JOINT CHANDRA-VLA OBSERVATION

- Joint *Chandra*/VLA observations to:
  - Obtain good X-ray position and spectrum
  - Detect the source in radio
  - Check accretion/ejection coupling in the first quiescent HMXB
- 60 ks obs with *Chandra* + 6 h obs with VLA (8 - 12 GHz)
- Expected radio flux density between 9 and 18 µJy
AT TeV ENERGIES

\[ E^2 \frac{dF}{dE} \text{ [ erg s}^{-1} \text{]} \]

- Radio EVN, 2011 January-February
- X-ray, 2013 June
- AGILE, 2010 July
- Fermi/LAT, 2010 July
- Fermi/LAT, 3.5 years
- MAGIC, 2013 June
X-RAY DATA ANALYSIS

• The non thermal luminosity in the 0.3-5.5 keV range is $L_X = (1.6^{+1.0}_{-0.9}) \times 10^{31}$ erg s$^{-1}$ $\equiv (3.1 \pm 2.3) \times 10^{-8} L_{\text{Edd}}$

• The value of non thermal luminosity is well below the threshold of $10^{-5} L_{\text{Edd}}$ set by Plotkin et al. (2013) to indicate the quiescent state of XRBs, making our results compatible with MWC 656 being in quiescence

• This is the first case of a detection of a HMXB with a BH in quiescence

• Might be interpreted as an ADAF which leads to the low X-ray luminosity
X-RAY DATA ANALYSIS

• Thermal component
  - Might be arising from the hot wind of the Be star
  - The luminosity of this component is compatible with the \(L_x/L_{\text{Bol}} \approx 10^{-7}\) relation from Cohen et al. (1997).
    Our results are \(L_x/L_{\text{Bol}} \approx 3 \times 10^{-7}\)

• Non thermal component
  - Photon index \(\Gamma = 1.0 \pm 0.8\) compatible with Plotkin et al. (2013)
  - Possible origin in the vicinity of the black hole
  - The non thermal luminosity in the 0.3-5.5 keV range is \(L_x = (1.6^{+1.0}_{-1.0}) \times 10^{31}\) erg s\(^{-1}\) \(\equiv (3.1 \pm 2.3) \times 10^{-8}\) \(L_{\text{Edd}}\)