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Hidden black holes in binaries

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In this talk I will present the results of **two recent publications** plus work in progress:

A Be-type star with a black-hole companion
J. Casares, I. Negueruela, M. Ribó, I. Ribas, J. M. Paredes, A. Herrero & S. Simón-Díaz
Nature, 505, 378 (2014)

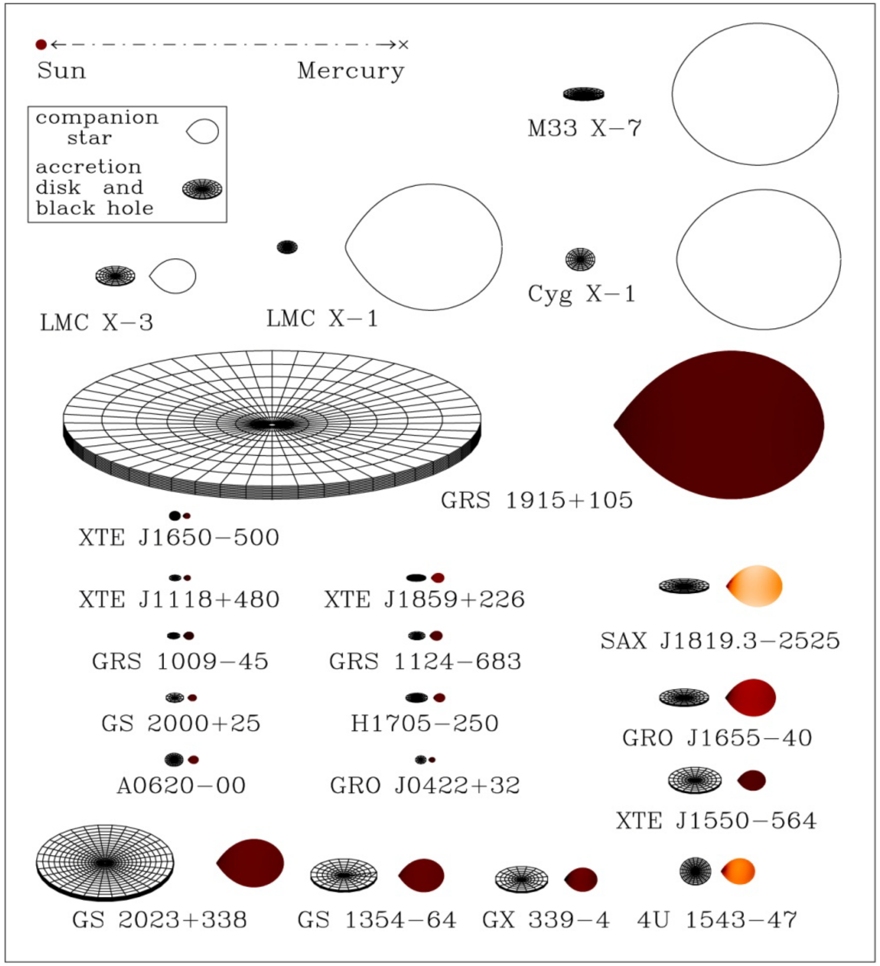
Discovery of X-ray emission from the first Be/black hole system
P. Munar-Adrover, J. M. Paredes, M. Ribó, K. Iwasawa, V. Zabalza, & J. Casares
ApJ, 786, L11 (2014)

OUTLINE

1. Introduction
2. Discovery of MWC 656, the first Be/BH binary
3. The missing Be/BH binary population and fate of MWC 656
4. The X-ray counterpart of MWC 656
5. Accretion/ejection coupling in quiescent HMXBs
6. Work in progress
7. Conclusions

Introduction

Dynamical black holes in binaries



McClintock et al. 2011 CQGra 28 114009

4 HMXBs

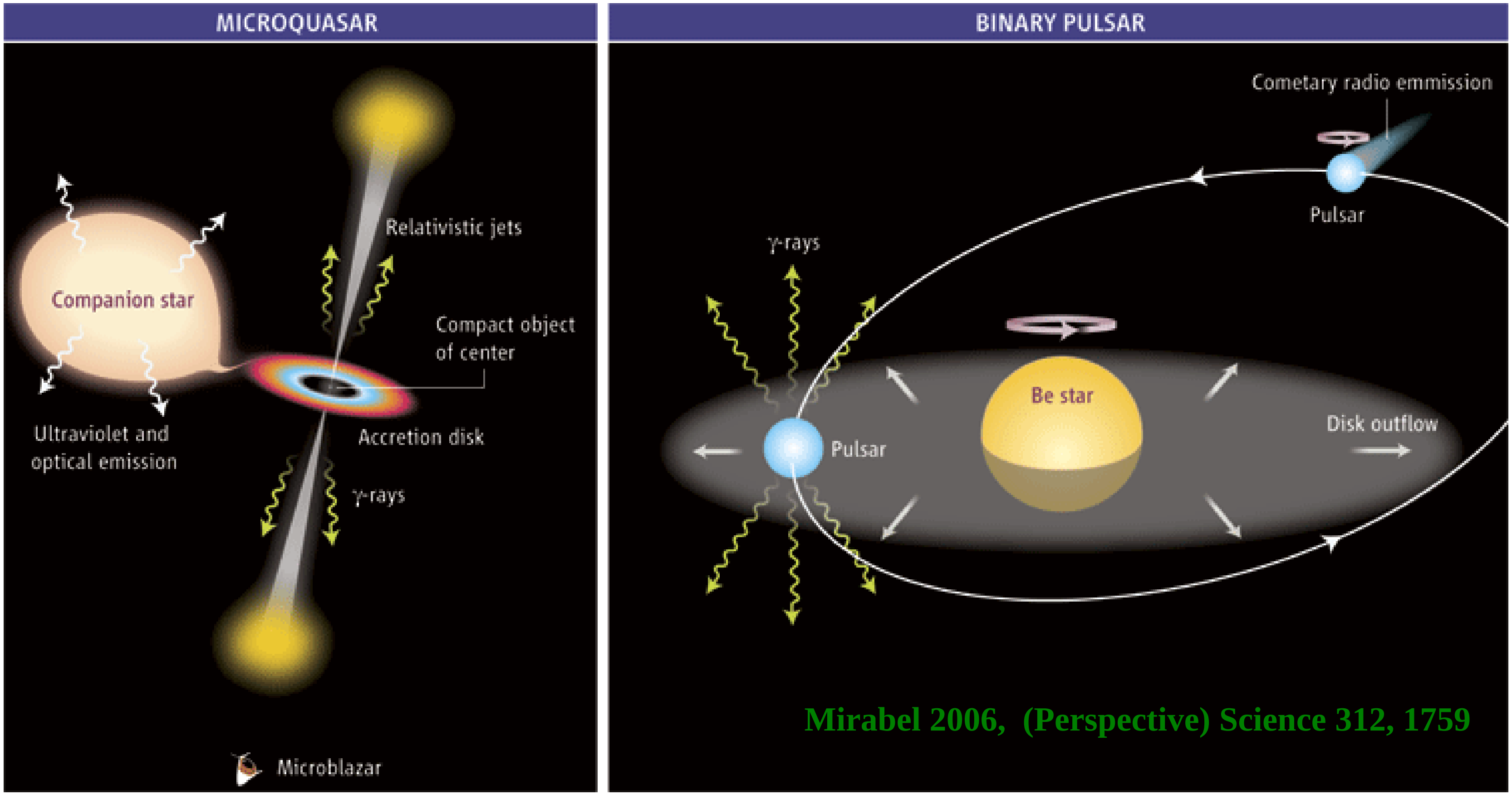
- Massive OB donors
- Wind fed
- X-ray persistent

17 XRTs

They show X-ray outbursts and different BH states

Introduction

Gamma-ray emitting binaries with compact objects

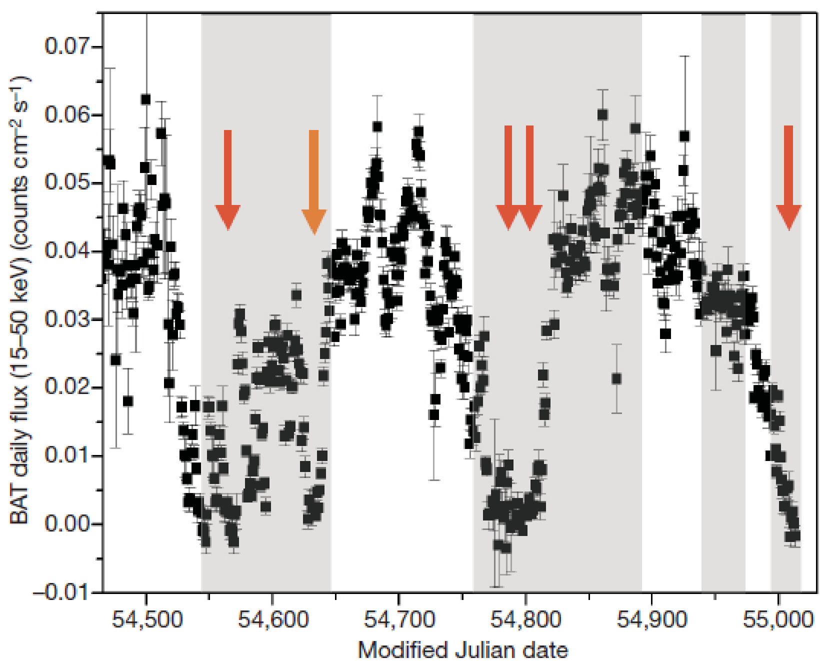


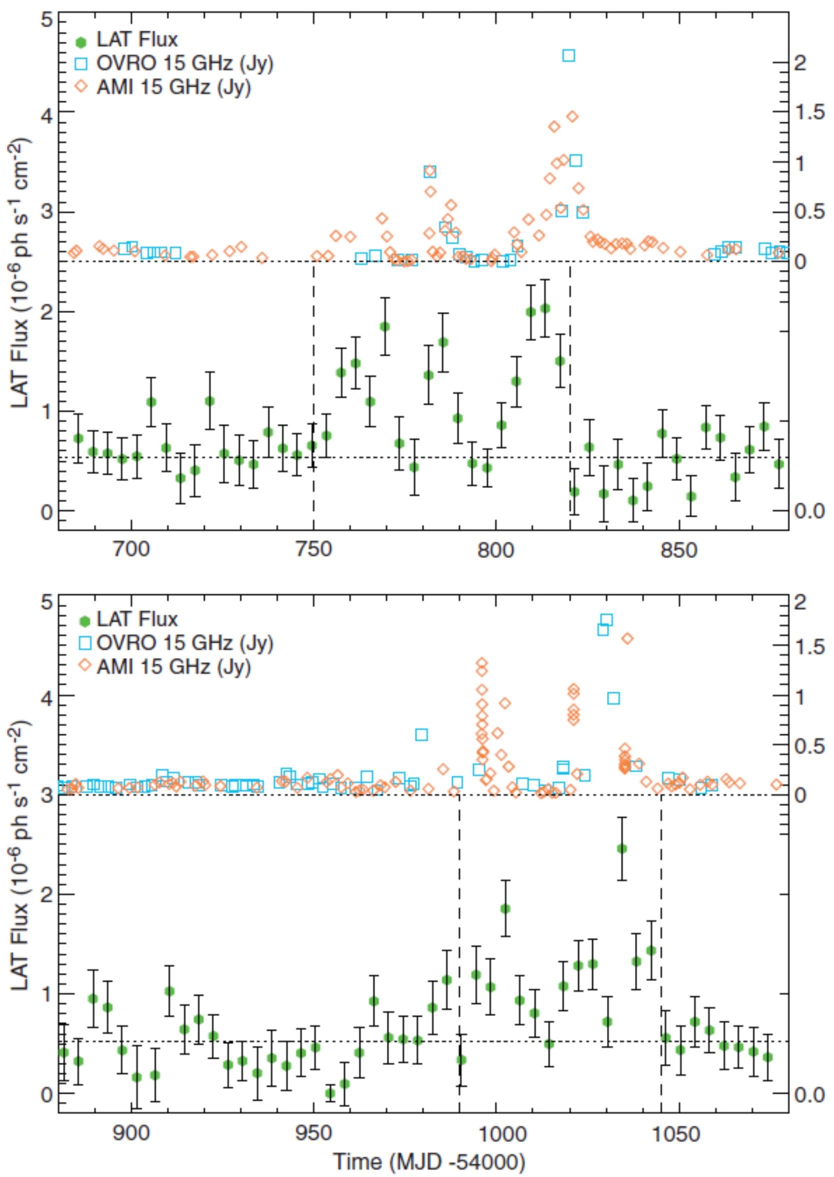
Cygnus X-3, Cygnus X-1

LS 5039 ? LS I +61 303 ? PSR B1259−63
HESS J0632+057 ?
1FGL J1018.6−5856 ?

Introduction

Microquasars like Cygnus X-3 or Cygnus X-1 show **transient HE gamma-ray emission** depending on the accretion **state of the source**, as detected by the *AGILE* and *Fermi* satellites **(Tavani et al. 2009, Abdo et al. 2009)**.

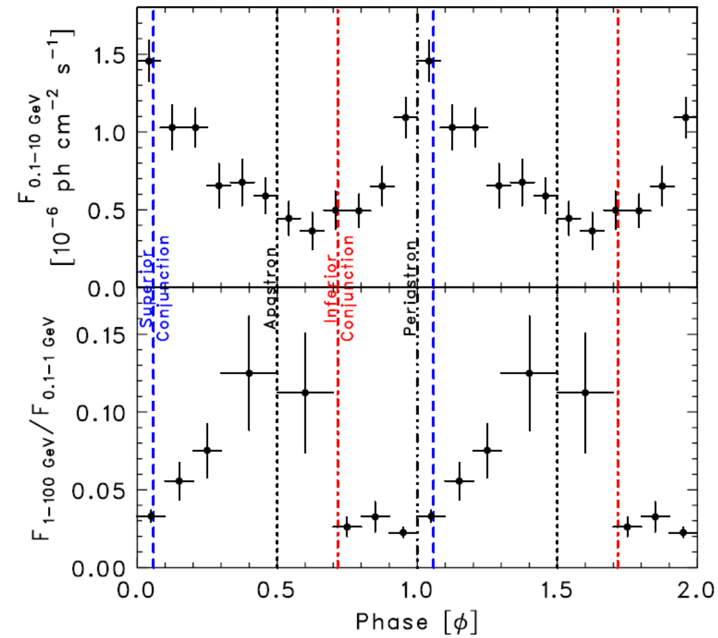




Introduction

Gamma-ray binaries show **variable HE gamma-ray emission**, either persistent or transient, but always linked to **orbital periodicity** (accretion or anisotropic IC).
LS I +61 303 (Abdo et al. 2009).
LS 5039 (Abdo et al. 2009).
PSR B1259-63 (Abdo et al. 2011).

LS 5039



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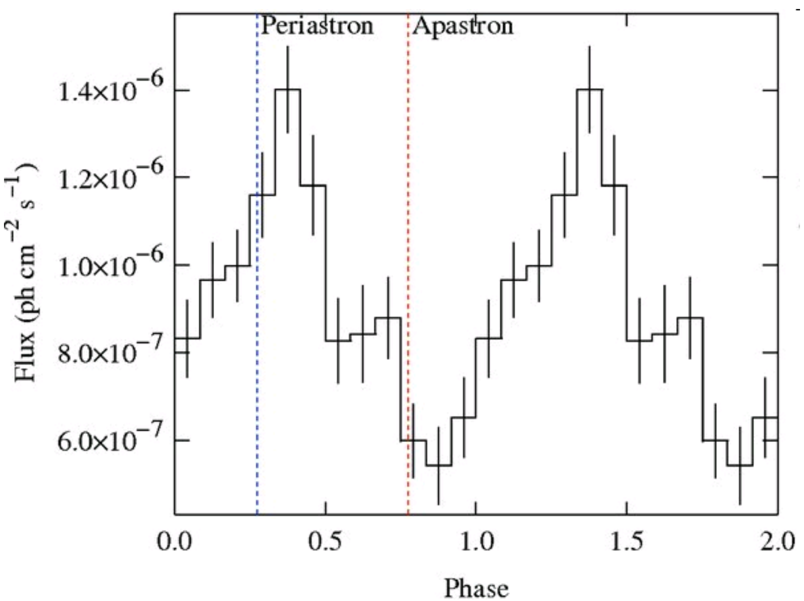
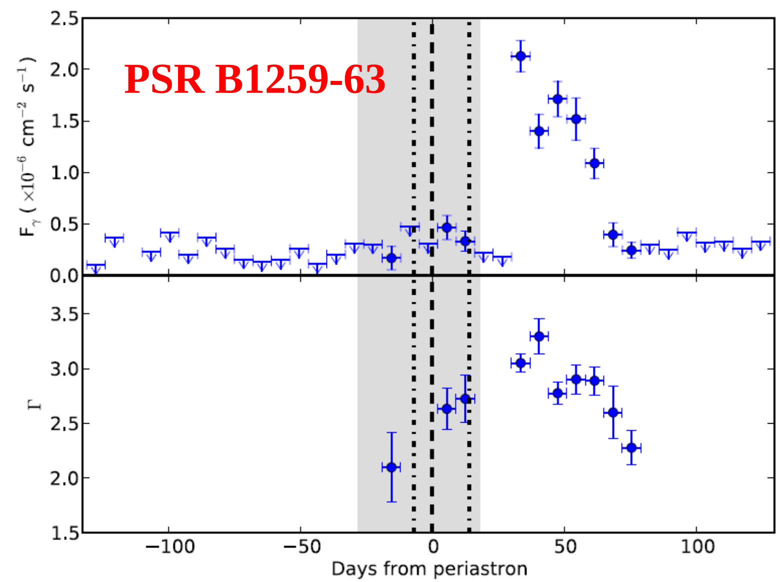




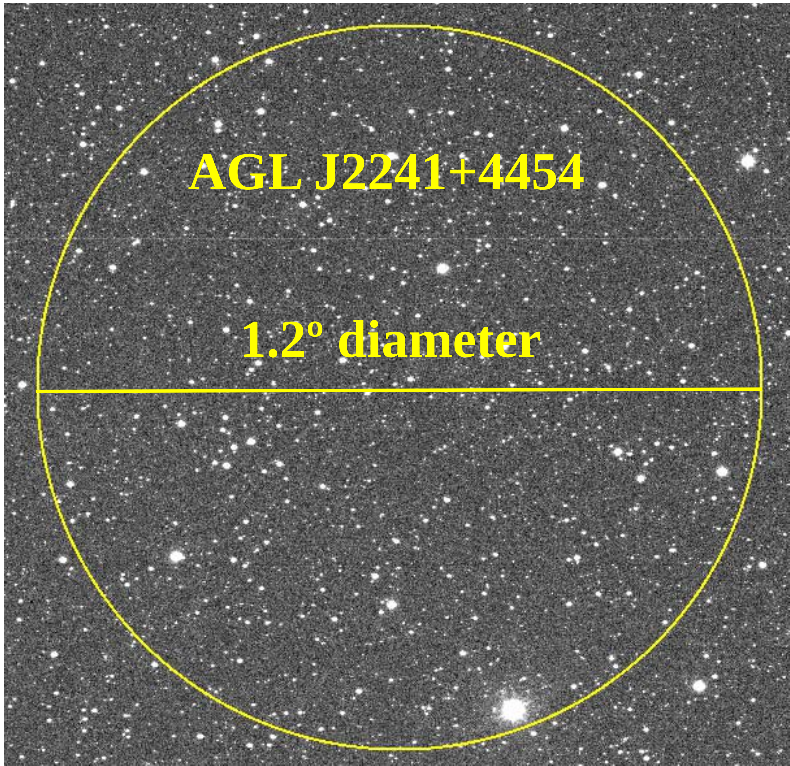
Discovery of MWC 656, the first Be/BH binary

AGILE detected a **new unidentified gamma-ray source: AGL J2241+4454**.

- **Coordinates** (l,b) = (100.0,**-12.2**) ± 0.6 deg (95% stat.) ± 0.1 deg (syst.).
- **Epoch of detection**: from 2010-07-25 01:00 UT to 2010-07-26 23:30 UT.
- **Flux**: a maximum likelihood analysis yields a detection at a significance level larger than 5 sigma, and a flux above 1.5 x 10^{-6} ph/cm^2/s (E > 100 MeV).

(Lucarelli et al. 2010, ATel # 2761).

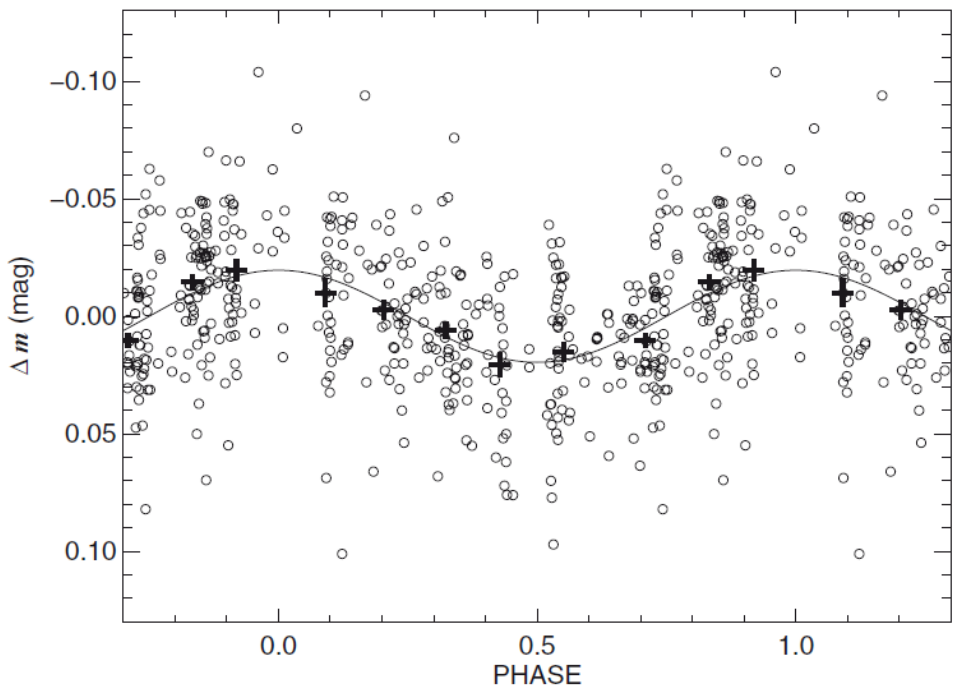
***Fermi*/LAT could not confirm** the detection. An upper limit (UL) of 10^{-7} ph/cm^2/s (95% CL) above 100 MeV was set, using Γ=2 for the data taken at the same time as the *AGILE* discovery **(http://fermisky.blogspot.com.es/2010/07/extra-note-july-30-2010.html)**.

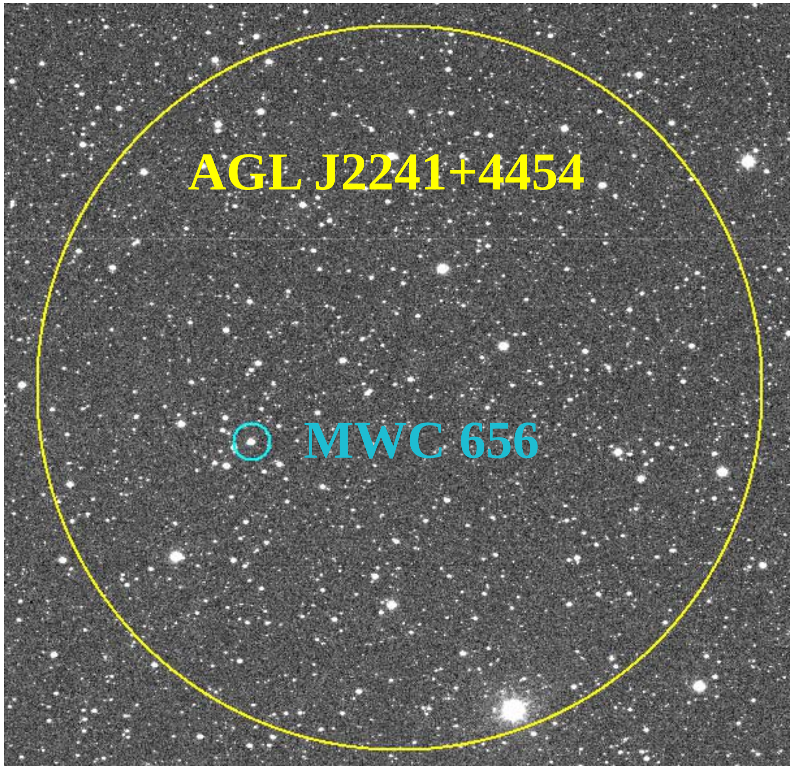


Even if it is outside the Galactic plane the position uncertainty is so large that **lots of possible counterparts are possible**.

Discovery of MWC 656, the first Be/BH binary

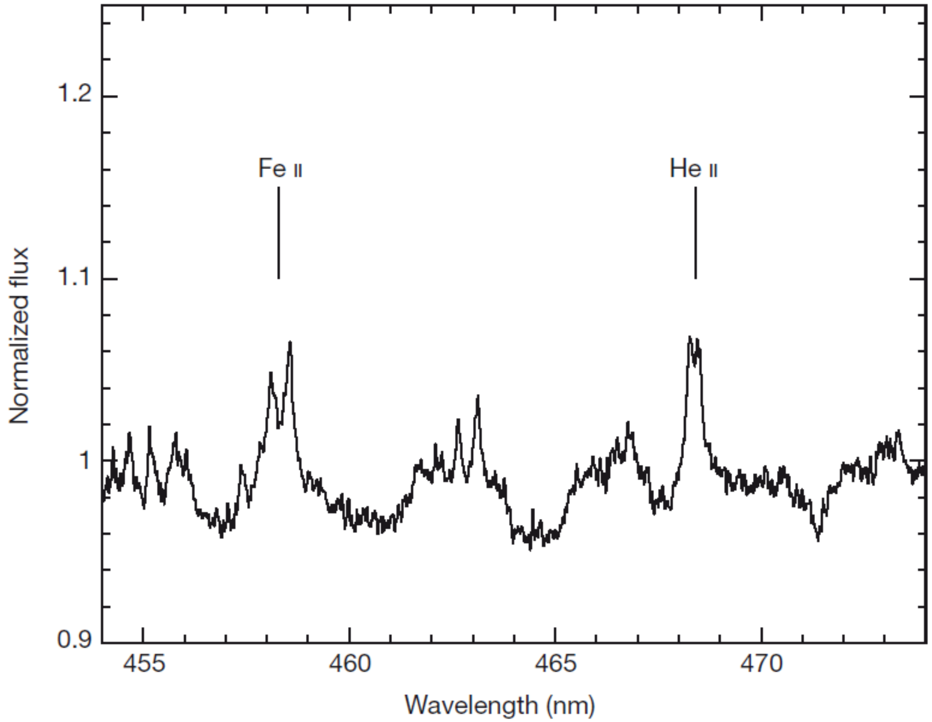
Williams et al. (2010) suggested two possible counterparts: the probable quasar RX J2243.1+4441 and **the Be star HD 215227**, aka **MWC 656**. These authors compiled optical photometry of MWC 656 from different archives and obtained a **periodicity of 60.37±0.04 days**, confirmed later with a coherent data set by **Paredes-Fortuny et al. (2012)**. Radial velocity studies by **Casares et al. (2012)** confirmed the binary nature of MWC 656, allowing for a NS or BH companion.





Discovery of MWC 656, the first Be/BH binary

We realized about the presence of a **HeII 4686A emission line**, which is remarkable because it **requires temperatures hotter than can be achieved in disks around B stars**. Further, the **HeII profile is double-peaked**, which is the signature of gas orbiting in a Keplerian geometry **(Casares et al. 2014)**.
FeII lines are originated in the **disk surrounding the B star** (decretion disk) and are less noisy than photospheric lines **(Casares et al. 2014)**.



Discovery

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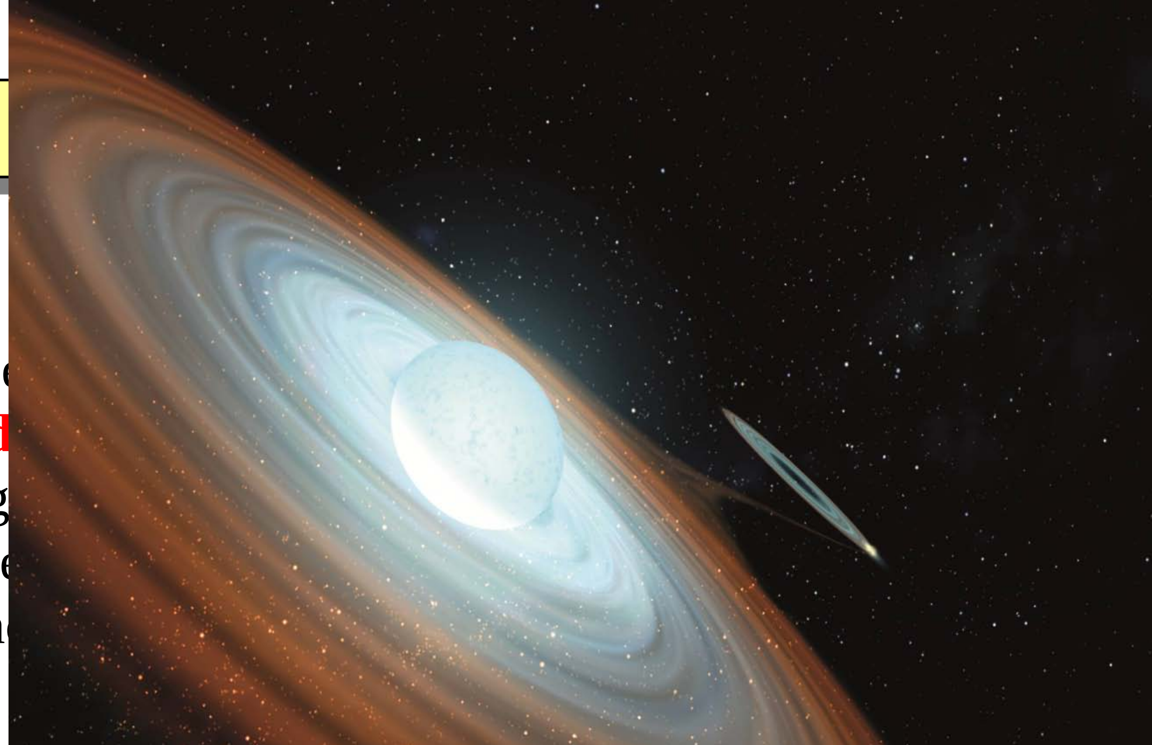
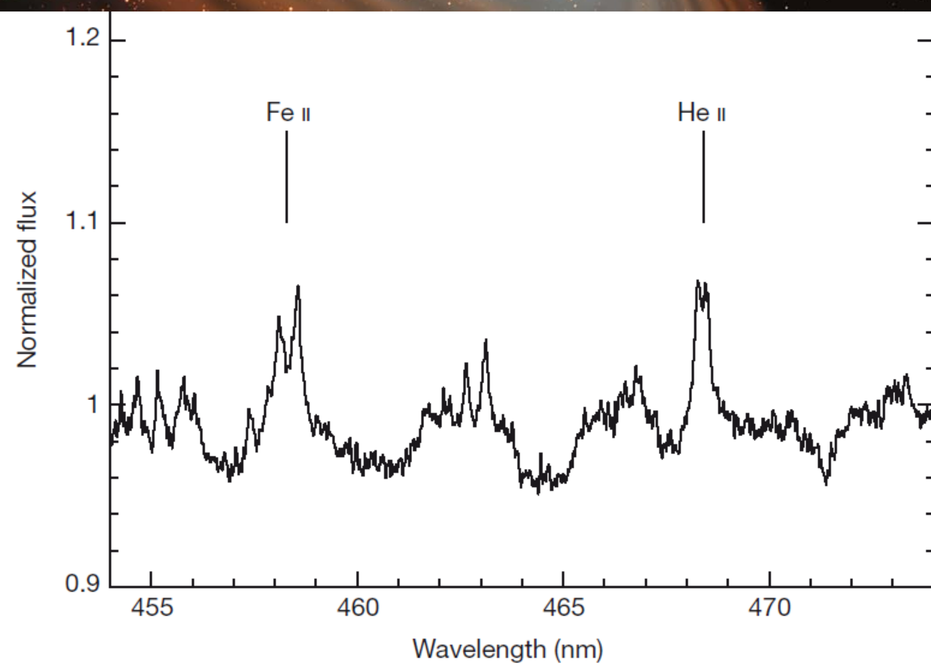
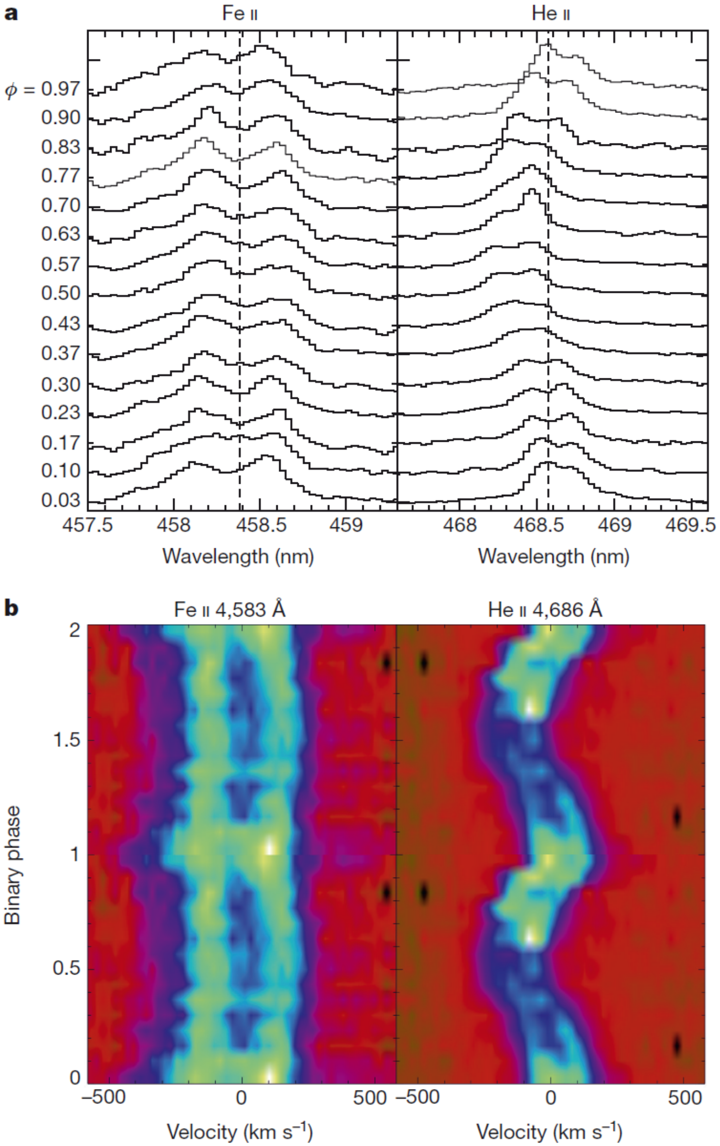




Discovery of MWC 656, the first Be/BH binary

The **FeII** and **HeII** lines both show **radial velocity variations with a periodicity of 60 d** (orbital period). The lines vary in antiphase, and the parameters reveal the **same time of periastron** and an **ω offset around 180º**, as expected if originated in two bodies orbiting each other **(Casares et al. 2014)**.

Parameter	He II $\lambda 4686$	Fe II $\lambda 4583$
$P_{\rm orb}$ (days)	60.37 (fixed)	60.37 (fixed)
T_0 (HJD−2,450,000)	3245.3±7.5	3243.1±3.7
e	0.08±0.06	0.24±0.08
ω (deg)	351.7±44.4	164.4±22.1
γ (km s^{-1})	−44.5±3.4	−13.5±1.8
K (km s^{-1})	78.8±4.6	31.0±2.4
$a \sin i$ ($R_\odot$)	93.7±5.4	35.9±2.8
$f(M)$ ($M_\odot$)	3.02±0.53	0.17±0.04
$\sigma_{\rm f}$ (km s^{-1})	19.2	10.3



Discovery of MWC 656, the first Be/BH binary

The **HeII double peak is distorted by an S-wave component**, typically associated with a bright spot or asymmetry in the outer accretion disk. This requires correction of the mean radial velocity for this line. Once this is taken into account, we can produce a **combined fit to all radial velocities to obtain the best orbital parameters**. This allows to obtain a **mass ratio** of 0.41+/-0.07 **(Casares et al. 2014)**.

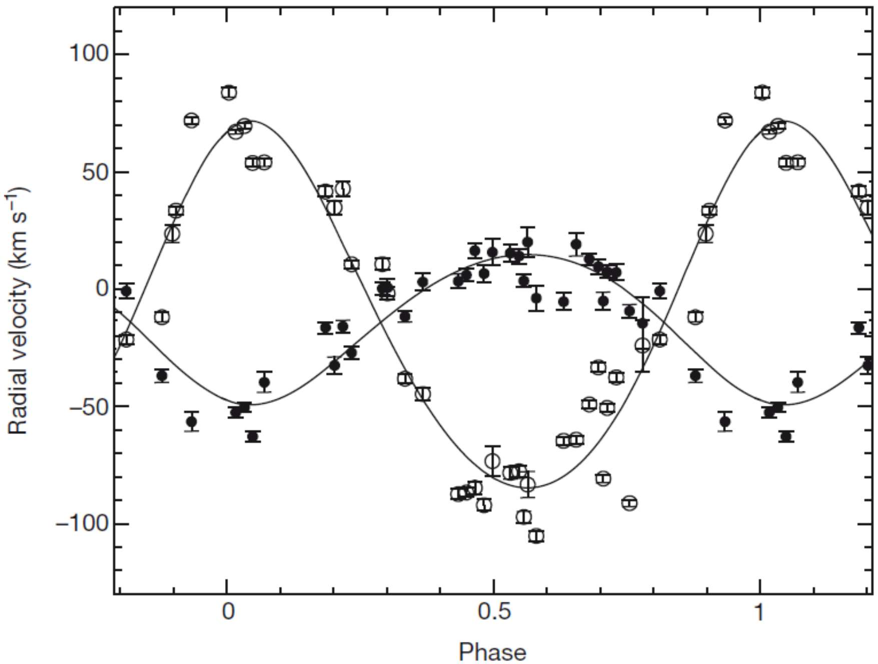


Table 1 | Orbital elements for MWC 656

Parameter	Value
P_{orb} (days)	60.37 (fixed)
T_0 (HJD − 2,450,000)	3,243.70 ± 4.30
e	0.10 ± 0.04
ω (degrees)	163.0 ± 25.6
γ (km s^{-1})	−14.1 ± 2.1
K_1 (km s^{-1})	32.0 ± 5.3
K_2 (km s^{-1})	78.1 ± 3.2
$a_1 \sin i$ ($R_\odot$)	38.0 ± 6.3
$a_2 \sin i$ ($R_\odot$)	92.8 ± 3.8
$M_1 \sin^3 i$ ($M_\odot$)	5.83 ± 0.70
$M_2 \sin^3 i$ ($M_\odot$)	2.39 ± 0.48
M_2/M_1	0.41 ± 0.07
σ_f (km s^{-1})	16.7

Discovery of MWC 656, the first Be/BH binary

A precise determination of the companion's mass requires an accurate spectral classification of the Be star. We determine a **spectral type of B1.5–B2**, and a **luminosity class III**.

Our adopted B1.5–B2 III classification implies a mass of **10–16 solar masses for the Be star**, and hence a **companion star of 3.8–6.9 solar masses**.

The large dynamical mass rules out a white dwarf or a neutron star, so **the only viable alternative is a black hole (Casares et al. 2014)**.

Using the optical photometry and the spectral classification and calibration we **derive a spectro-photometric distance of 2.6+/-0.6 kpc**.

Analysis of archival *ROSAT* images yields an upper limit to the X-ray flux which translates into an **X-ray luminosity < 1.0×10^{32} erg s^{-1} or < 1.6×10^{-7} L_{Edd}**. Therefore, **accretion is highly inefficient in MWC 656**, akin to accretion onto black holes in quiescent low-mass X-ray binaries.

The missing Be/BH binary population and the fate of MWC 656

Binary population synthesis models predict a high number of Be/NS systems and a low number of Be/BH systems. **The ratio of Be/NS to Be/BH varies between 10 and 50** depending on the survival after the Common Envelope phase and on the kick velocities for neutron stars **(Belczynski & Ziolkowski 2009)**.

Simulations: Be X-ray Binary Formation Channels

Formation Channel	Efficiency (%)[a] Model A	(B)	[C]	Evolutionary History[b]
BeNS:01	44.2	(41.8)	[45.3]	CE:a→b, SN:a
BeNS:02	42.3	(43.9)	[45.0]	CE:a→b, NC:a→b, SN:a
BeNS:03	11.9	(13.3)	[8.8]	NC:a→b, SN:a
BeNS:04	1.6	(1.0)	[0.9]	All other
BeBH:01	79.6	(13.2)	[17.2]	CE:a→b, SN:a
BeBH:02	19.8	(85.5)	[82.8]	NC:a→b, SN:a
BeBH:03	0.6	(1.3)	[0.0]	All other
$N_{\rm BeNS}$	579	(517)	[1578]	Galactic number of NS BeXRBs
$N_{\rm BeBH}$	82	(19)	[29]	Galactic number of BH BeXRBs
$F_{\rm NStoBH}$	7	(27)	[54]	Number ratio of NS to BH BeXRBs

Notes.
[a] Efficiency for models with standard kicks ($\sigma = 265$ km s^{-1}) in which survival through a CE phase with an HG donor is allowed (A) and not allowed (B). Model C shows results for evolution with small kicks ($\sigma = 133$ km s^{-1}) and the survival in CE with HG donors is not allowed.

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There are currently **81 BeXBs known in the Galaxy with 48 pulsating NS**, and thus our discovery of a BH companion to MWC656 is consistent with these model predictions. However, it should be noted that the X-ray spectra of the remaining BeXBs, whenever they are available, also indicate the presence of a NS. Further, in stark contrast with the known BeXBs, MWC656 has been identified through a claimed gamma-ray flare and not by its X-ray activity. This seems to imply **that the discovery of Be/BHs is observationally biased, in which case common envelope mergers would be less frequent than commonly assumed and/or NS kicks would be best described by the radio pulsar birth velocity distribution (Casares et al. 2014)**.

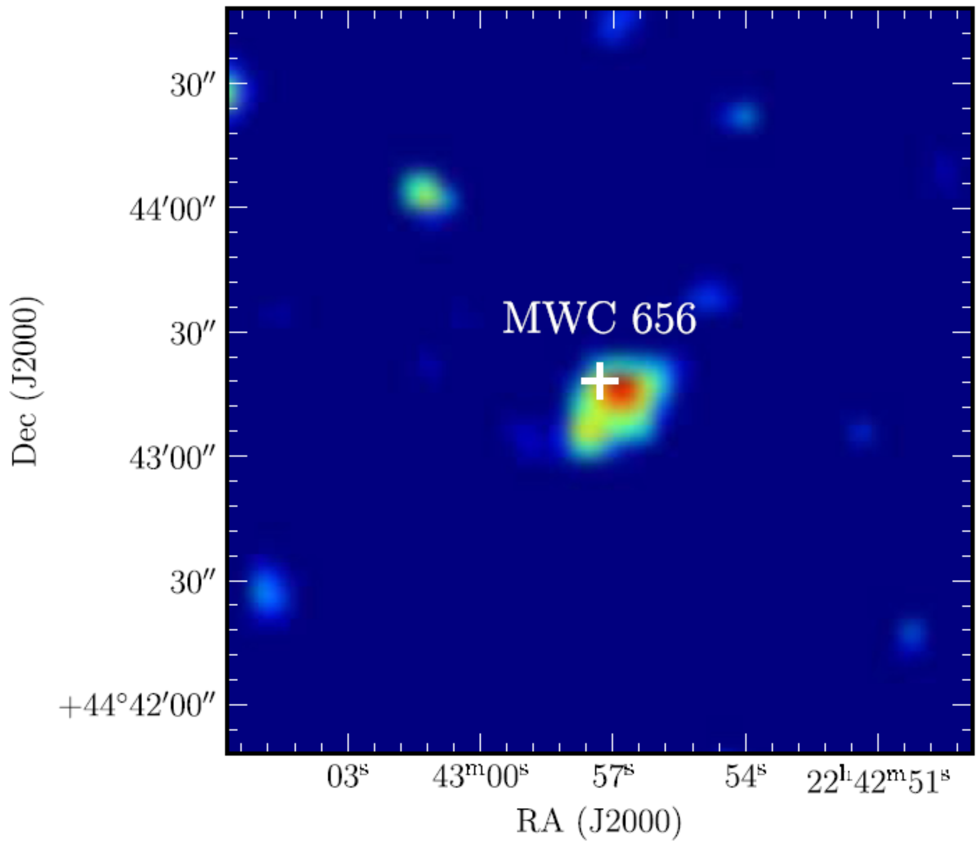
The missing Be/BH binary population and the fate of MWC 656

A candidate black-hole/neutron-star progenitor.
Last, it is interesting to note that MWC656 will **probably evolve into a black-hole/neutron-star binary**. During the red giant phase the Be star will expand and engulf the BH. Mass transfer will be dynamically unstable and a common envelope will ensue. This is a highly dissipative process which leads to **spiral-in of the BH, efficient circularization of the orbit and the ejection of the Be star envelope**. The outcome of the common envelope phase will then be a 2.9 solar-mass He star and the present 5 solar-mass BH companion in a close circular orbit. After the **core collapse of the He star a NS will be formed**, which might remind bound to the BH depending on the acquired kick.
BH/NS binaries, which have not yet been detected, are instrumental in providing **fundamental tests of gravitational theories, strong sources of gravitational waves and prime candidates for the production of short gamma-ray bursts through coalescence**. The fate of MWC656 as a possible BH/NS binary is very relevant because it provides tight empirical constraints on detection rates for gravitational wave observatories, such as advanced LIGO/VIRGO.
(Casares et al. 2014).

The X-ray counterpart of MWC 656

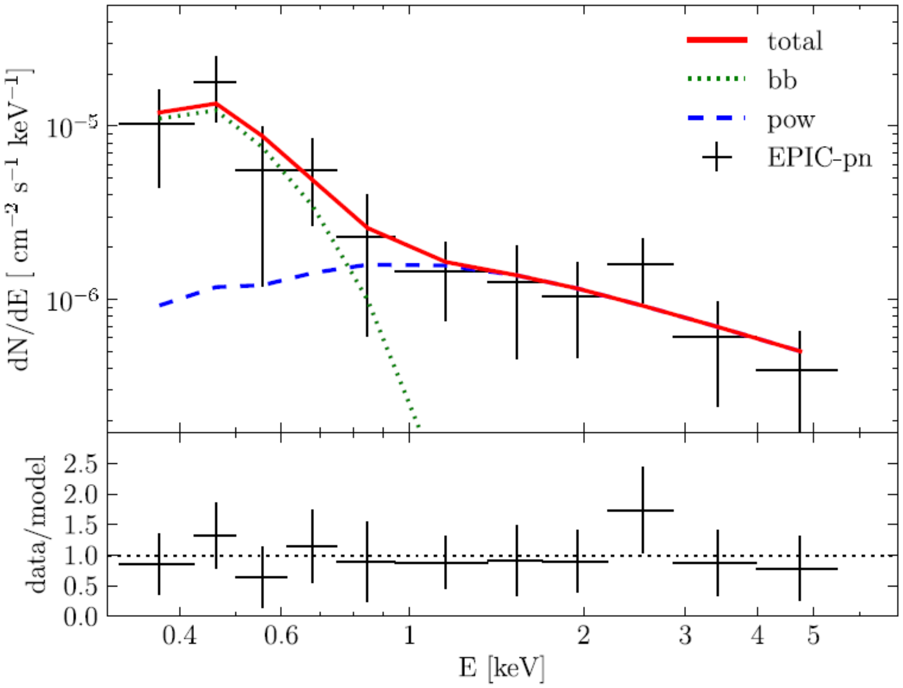
We conducted a 14-ks ***XMM-Newton*** observation of MWC 656 on 2013 June 4. We **detect a faint source** at 4.4σ coincident with MWC 656. The X-ray position is compatible with the Hipparcos position of MWC 656 at 2.4σ.
The source is **only detected in the low-energy range** of the EPIC-pn detector, between 0.3 and 5.5 keV.

EPIC-pn camera image at the position of MWC656 in the 0.3–5.5 keV energy band, smoothed using a Gaussian interpolation with a 2” kernel.



The X-ray counterpart of MWC 656

***XMM-Newton* EPIC-pn spectrum** in the 0.3–5.5 keV energy range (data points) overplotted with the fitted absorbed **blackbody** (green dotted line) plus a **power-law** (blue dashed line) model. Thermal dominates < 0.8 keV. C-statistic used due to low number of counts.



X-Ray Spectral Fit Parameters of MWC 656

Model[a]	Parameters		F(0.3–5.5 keV)/10^{-14} (erg cm^{-2} s^{-1})			C-statistic	Comments
	$k_B T$ (keV)	Γ	Thermal	Non-thermal	Total		
pow	–	$2.0^{+1.0}_{-0.8}$	–	$2.3^{+0.8}_{-0.7}$	$2.3^{+0.8}_{-0.7}$	14.6	Deviations at ~0.5, ~1.0, ~2.5 keV
bb	$0.12^{+0.07}_{-0.05}$	–	$2.0^{+0.9}_{-0.8}$	–	$2.0^{+0.9}_{-0.8}$	31.4	No good fit above 1.5 keV
bb+pow	$0.07^{+0.04}_{-0.03}$	1.0 ± 0.8	$2.6^{+3.0}_{-1.4}$	$2.0^{+0.8}_{-0.7}$	$4.6^{+1.3}_{-1.1}$	2.8	Good fit (used in this work)
diskbb+pow	$0.09^{+0.04}_{-0.06}$	1.0 ± 0.8	$2.7^{+3.4}_{-1.4}$	$2.0^{+0.8}_{-0.7}$	$4.7^{+1.4}_{-1.1}$	2.8	Good fit

The X-ray counterpart of MWC 656

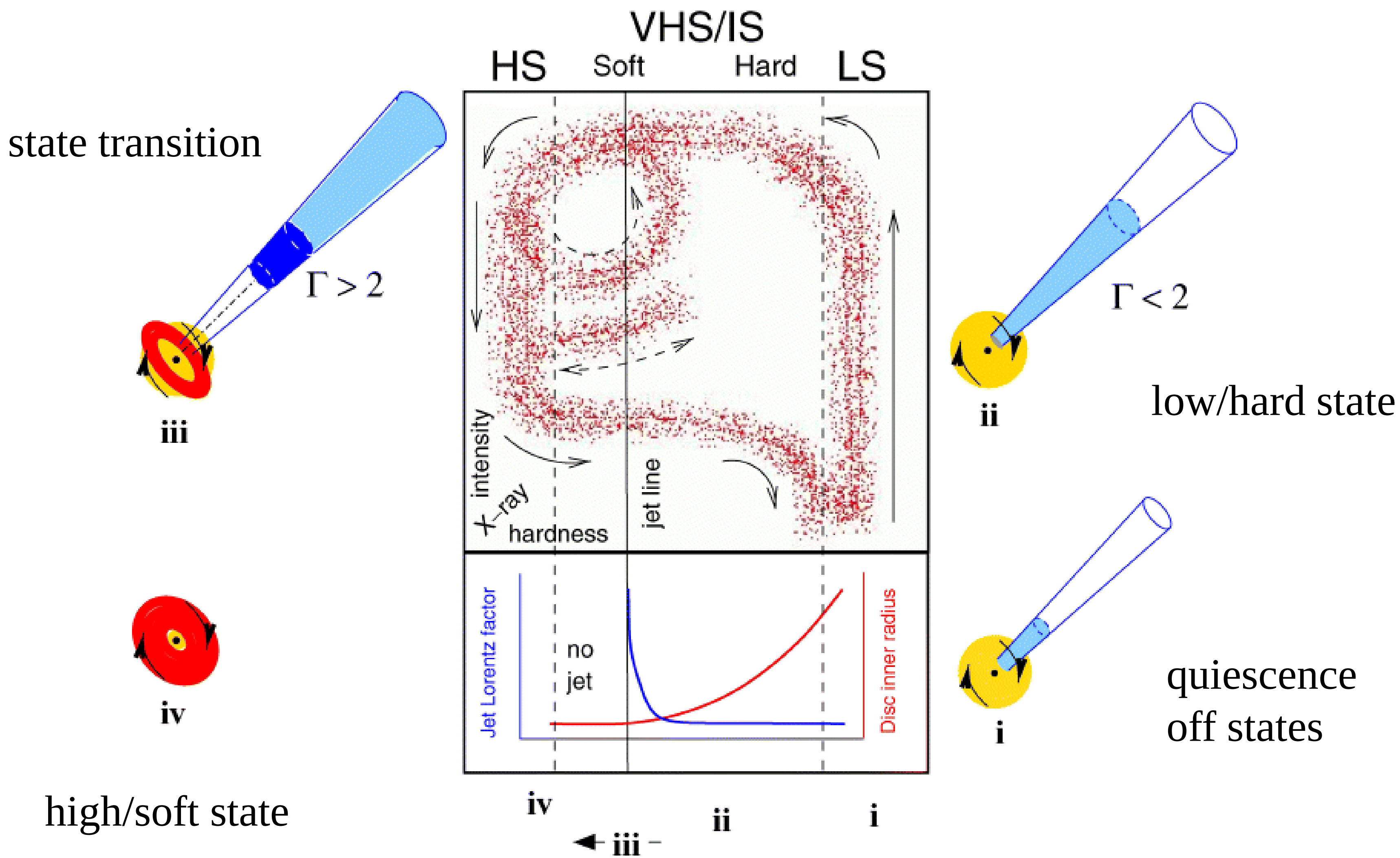
Thermal and non-thermal X-ray emission.

From the L_{bol}=7×10^{37} erg s^{-1} and the **thermal X-ray luminosity** we obtain L_X/L_{bol} = 3×10^{-7}, **compatible within uncertainties** with the correlation $L_X \sim 10^{-7} L_{bol}$ for **isolated B stars (Berghoefer et al. 1997; Cohen et al. 1997)**.
The obtained results suggest that **the thermal component of our X-ray spectrum arises from the hot wind of the Be star**.

The **non-thermal X-ray luminosity** of MWC 656 in the 0.3–5.5 keV band is L_X = (3.1 ± 2.3) × $\mathbf{10^{-8} L_{Edd}}$ for the estimated BH mass of 3.8–6.9 solar masses (Casares et al. 2014). This luminosity is around three orders of magnitude below the $10^{-5} L_{Edd}$ threshold from Plotkin et al. (2013), **making our results compatible with MWC 656 being in quiescence**.

In summary: the thermal component is associated with the hot wind of the Be star, whereas the power-law component is associated with emission from the vicinity of the BH **(Munar-Adrover et al. 2014)**.

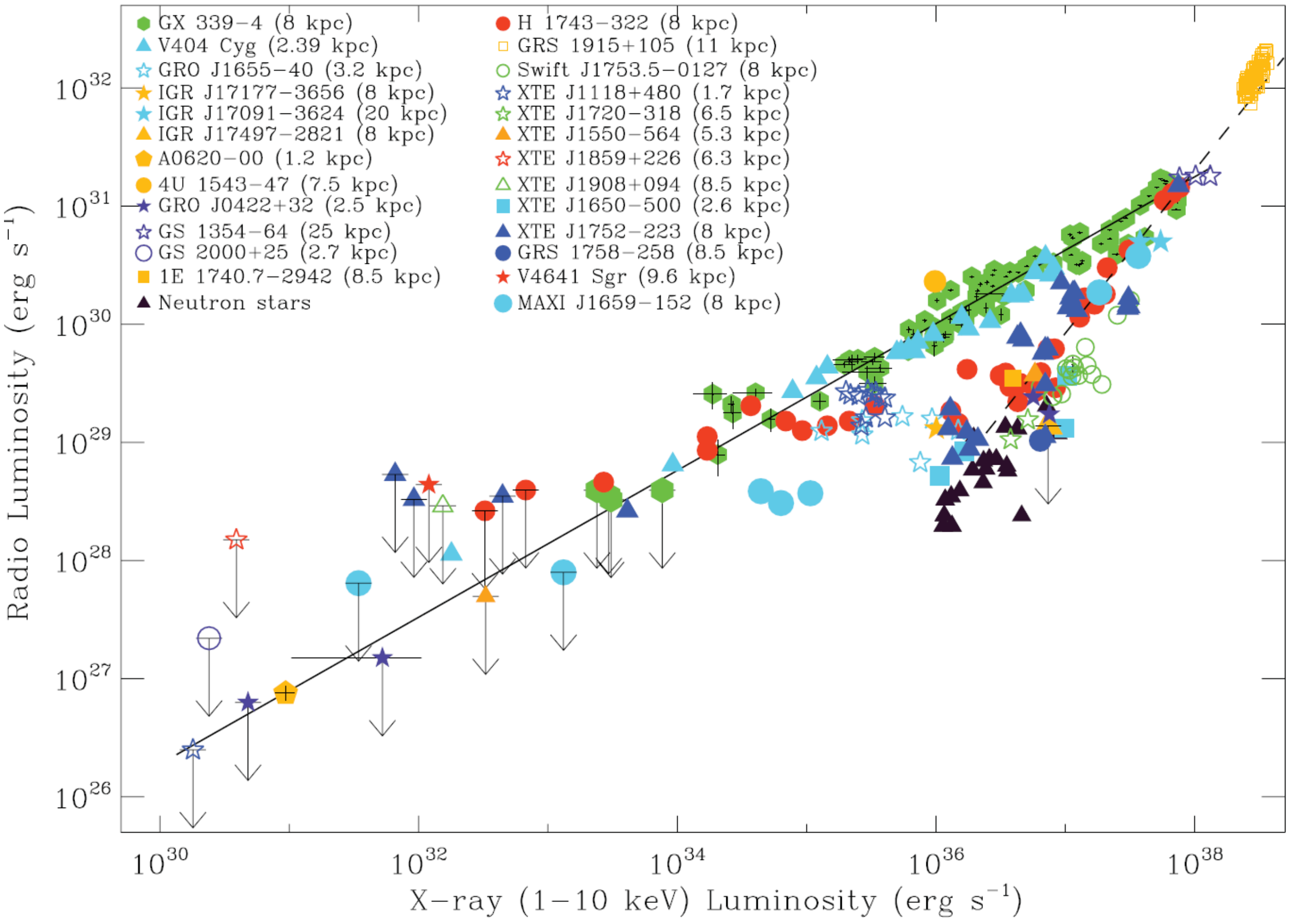
Accretion/ejection coupling in quiescent HMXBs



(Fender et al. 2004)

Accretion/ejection coupling in quiescent HMXBs

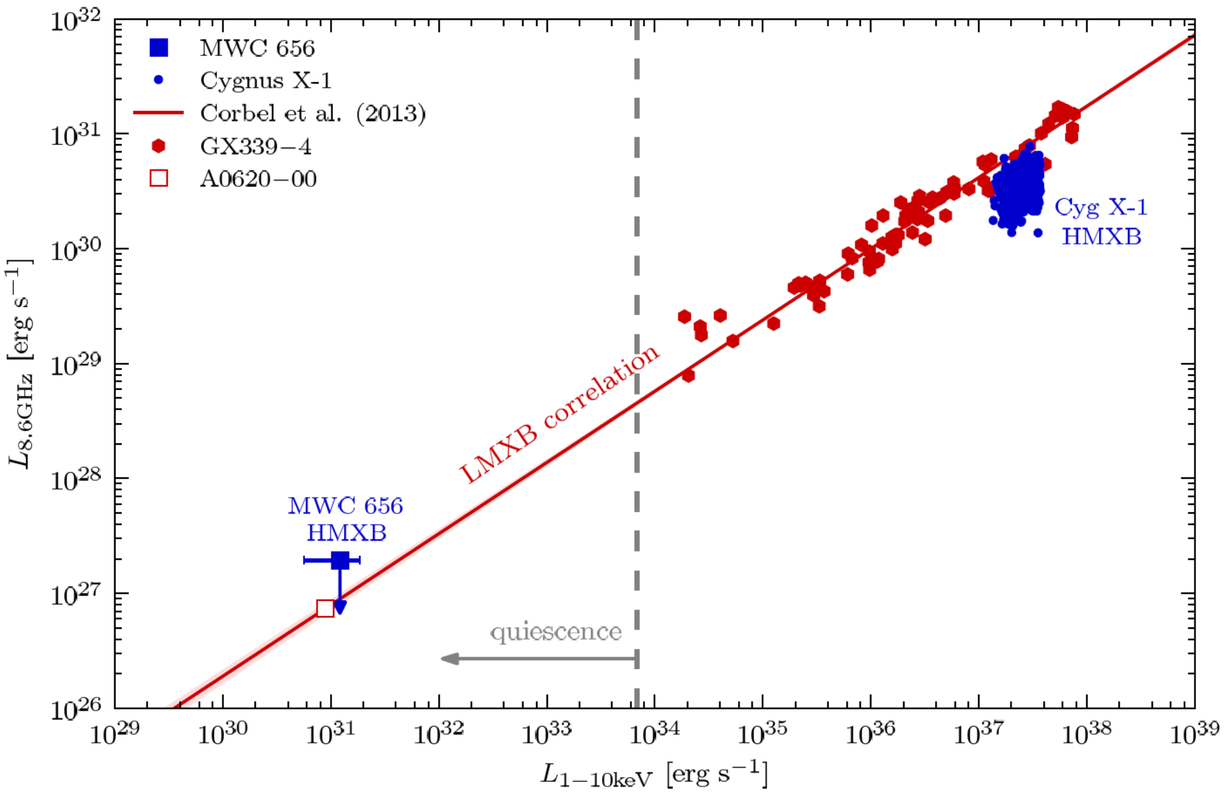
There is a **well-known radio/X-ray correlation for LMXBs** in the quiescent and low-hard states **(Corbet et al. 2013)**.



Accretion/ejection coupling in quiescent HMXBs

Using non-simultaneous radio flux density upper limits we find that **MWC 656 is located in the lower-left side of the luminosity diagram**, in a region where it may be consistent with and just above the correlation from Corbel et al. **(Munar-Adrover et al. 2014)**. Consequently, **the radio/X-ray correlation might also be valid for BH HMXBs**.

MWC 656 will allow the study of accretion processes and of accretion/ejection coupling **at very low luminosities for BH HMXBs**.



Work in progress

- We are **checking the *AGILE* data of MWC 656** for other possible HE gamma-ray flares.

- We have conducted **MAGIC observations** in 2012 (López-Oramas et al. 2013) and 2013 (simultaneous to *XMM-Newton*) to search for TeV emission.

- We are obtaining **new optical spectroscopy to improve the orbital parameters** of the binary system. We are **monitoring the optical photometry to improve the orbital period** (and thus the orbital parameters).

- We are using **binary population synthesis** to predict the fate of MWC 656.

- We have submitted a **Joint Chandra/VLA** proposal to obtain a good X-ray spectrum, detect the source in radio and **check the accretion/ejection coupling in the first quiescent HMXB**.

- We are **searching for other Be/BH candidates**, also checking *AGILE* data.

Conclusions

- We have **discovered the first Be/BH binary system** thanks to *AGILE* alert.

- **Be/BH binaries may be more abundant than predicted by Binary Population Synthesis models**.

- This binary will probably evolve into a **BH/NS binary** that would emit **gravitational waves during coalescence** in a short gamma-ray burst.

- We have discovered that **the first Be/BH binary is an X-ray binary** in quiescence. It **might fulfill the radio/X-ray correlation found for LMXBs**, and thus have a similar **accretion/ejection coupling**.

- This opens the door for the **study** of accretion and accretion/ejection coupling in **BH HMXBs at low luminosities**.

- Is there a population of **hidden black holes? Will *AGILE* help to find them?**

Conclusions

Be/BH binaries may be more abundant than predicted by Binary Population Synthesis models. Will *AGILE* help to find them?