**LETTER TO THE EDITOR**

**Detection of variable VHE γ-ray emission from the extra-galactic γ-ray binary LMC P3**

T. Garrigoux, J.-P. Ernenwein, L. Rinchiuso, F. Schüssler

1. Introduction

More than 60% of all stellar systems containing high-mass stars (spectral type B2 or earlier) are binary or multiple systems (Duchêne & Kraus 2013). When the more massive stars in these systems end its life in a supernova explosion, a binary system is left behind where a compact object, either a neutron star or a black hole, is orbiting the remaining star. If these objects radiate most of their power at energies of more than 1 MeV then they are called γ-ray binaries. The γ-ray emission arises either from the interaction of a pulsar wind (driven by the rotational energy loss of a rotating neutron star) with the stellar wind, or from accretion of the stellar wind onto a black hole or neutron star. The companion stars in these systems are either O- or B-type stars. Only six γ-ray binaries have been identified so far.

Received 6 December 2017 / Accepted 4 January 2018

**ABSTRACT**

Context. Recently, the high-energy (HE, 0.1–100 GeV) γ-ray emission from the object LMC P3 in the Large Magellanic Cloud (LMC) has been discovered to be modulated with a 10.3-day period, making it the first extra-galactic γ-ray binary.

Aims. This work aims at the detection of very-high-energy (VHE, >100 GeV) γ-ray emission and the search for modulation of the VHE signal with the orbital period of the binary system.

Methods. LMC P3 has been observed with the High Energy Stereoscopic System (H.E.S.S.); the acceptance-corrected exposure time is 100 h. The data set has been folded with the known orbital period of the system in order to test for variability of the emission.

**Results.** VHE γ-ray emission is detected with a statistical significance of 6.4σ. The data clearly show variability which is phase-locked to the orbital period of the system. Periodicity cannot be deduced from the H.E.S.S. data set alone. The orbit-averaged luminosity in the 1–10 TeV energy range is $(1.4 \pm 0.2) \times 10^{37} \text{ erg s}^{-1}$. A luminosity of $(5 \pm 1) \times 10^{37} \text{ erg s}^{-1}$ is reached during 20% of the orbit. HE and VHE γ-ray emissions are anti-correlated. LMC P3 is the most luminous γ-ray binary known so far.

**Key words.** gamma rays: stars -- binaries: general -- stars: massive

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They found that the high-energy (HE, 0.1–100 GeV) γ-ray signal of LMC P3, an unidentified γ-ray source located in the Large Magellanic Cloud (LMC; Ackermann et al. 2016), is periodic with a period of 10.301 ± 0.002 days. In this publication, the phase zero of this system is defined to correspond to the maximum of the HE γ-ray emission at MJD 57 410.25 ± 0.34. The position of LMC P3 is consistent with the one of the soft X-ray source CAL 60 (Long et al. 1981). Crampton et al. (1985) identified a star of spectral type O5 III(f) as the likely counterpart of this X-ray source. Subsequent X-ray observations with XMM-Newton (Bamba et al. 2006) and Chandra (Seward et al. 2012) already concluded from the variabilities of the X-ray flux and the radial velocity of Balmer absorption lines that this object is likely a binary system. LMC P3 is located in the supernova remnant DEM L241, making it the third X-ray binary found in an observable supernova remnant after SS433/W50 (Dubner et al. 1998) and SXP 1062 (Hénault-Brunet et al. 2012).

Little is known about the orbital parameters of the system. The most precise measurement of the orbital period comes from the HE γ-ray emission. Corbet et al. (2016) also analysed the radial velocity of the star and found an orbital period of 10.1 days and a superior conjunction of the companion star at MJD 57 408.61 ± 0.28. The mass function prefers a neutron star as the compact object for a wide range of inclinations, but a black hole cannot be ruled out. The X-ray and radio emission of this object is modulated with the 10.3-day period, but is out of phase with the γ-ray emission (Corbet et al. 2016).

The detection of periodic γ-ray emission from a system with an O5-type companion star and the γ-ray to X-ray luminosity ratio allow a clear classification of this object as a high-mass γ-ray binary (Corbet et al. 2016). It is the first such object discovered outside the Milky Way. With an HE γ-ray luminosity in the energy range from 200 MeV to 100 GeV of 2.5 × 10^{36} \text{erg s}^{-1} (Ackermann et al. 2016) it is also the most luminous γ-ray binary known so far.

2. H.E.S.S. observations and results

The LMC has been observed extensively with the High Energy Stereoscopic System (H.E.S.S.) since 2004. These observations led to the discovery of three individual very-high-energy (VHE, >100 GeV) γ-ray-emitting sources (H.E.S.S. Collaboration et al. 2012, 2015a). H.E.S.S. is a system of five Imaging Air Cherenkov Telescopes, located in the Khomas Highland of Namibia at an altitude of 1800 m. It is sensitive to γ rays of energies from tens of GeV up to several tens of TeV. The arrival direction of individual γ rays can be reconstructed with an angular resolution of better than 0.1°, and their energy is estimated with a relative uncertainty of 15%. The data discussed here were taken between 2004 and the beginning of 2016 and add up to a total observation time of 277 h, almost 70 h more than what was used in the previous publication of LMC sources (H.E.S.S. Collaboration et al. 2015a). After correcting for dead time and camera offset angles, the effective (on-axis equivalent) exposure time for LMC P3 is 100 h. About 5% of these observations were taken with the participation of the large H.E.S.S.-II telescope. The data recorded with this telescope are ignored in this analysis in order to obtain a homogeneous data set. The data were analysed using Model analysis with high-resolution cuts (de Naurois & Rolland 2009), where the camera images are compared with a semi-analytical model using a log-likelihood minimisation technique. The results were cross-checked with an independent multi-variate analysis chain based on image parametrisation (Ohm et al. 2009; Lu 2013). The background was estimated from rings around the on regions to generate the γ-ray images (ring background, Berge et al. 2007) and from test regions with similar offsets from the camera centre for the spectral analysis (reflected background, Berge et al. 2007). Due to the large zenith and offset angles as well as the event selection cuts the energy threshold for this data set is 714 GeV.

At the nominal position of CXOU J053600.0−673507 an excess of 76.3 γ-ray events is detected with a statistical significance of 6.4 σ (Table 1). The sensitivity of H.E.S.S. does not allow a detection of flux variations of the object on a nightly basis. Therefore, the nightly light curve of the emission does not show any sign of variability; the fit of a constant yields χ^2 = 75.3 for 99 degrees of freedom. The search for periodic emission using a Lomb–Scargle test (Lomb 1976; Scargle 1982) and the Z-Transformed Discrete Correlation Function (Alexander 1997) does not show significant periodicity. Figure 1 shows the light curve folded with the orbital period of the system of 10.301 days, where orbital phase zero is defined as the maximum of the HE light curve at MJD 57 410.25 (Corbet et al. 2016). Significant emission is detected only in the orbital phase bin between 0.2 and 0.4 with a pre-trial significance of 7.1 σ. This corresponds to a post-trial significance of 6.9 σ after correcting for the test of five independent phase bins. All other phase bins do not show significant emission (significances less than 2.5 σ, see Fig. 1). All phase bins have roughly the same exposure (between 18 and 21 h). Fitting the folded light curve with a constant results in a χ^2 value of 27.03 for 4 degrees of freedom. The χ^2 probability that the folded light curve is constant is hence less than 1.95 × 10^{-5}. The emission is clearly variable and it is phase-locked to the orbital period of the system. Therefore, the detected VHE γ-ray emission can be associated to the binary system LMC P3.

Figure 2 shows the VHE γ-ray excess maps in the on-peak (orbital phase 0.2 to 0.4) and the off-peak (orbital phase 0.4 to 1.2) parts of the orbit. Fitting a point-like source folded with the instrument’s point spread function results in a best-fit position of the source at RA = 05^h36^m00^s, Dec = −67°35′11″, equinox J2000, with a statistical uncertainty of ±23″ in each direction; the source is hence labelled HESS J0536–675. The best-fit position
the Klein–Nishina regime and a hard electron spectrum with an
of inverse Compton (IC) upscattering of stellar photons. A typical
stellar wind. The relativistic electrons produce
of the pulsar or in the shock front between the pulsar wind and
object. In
γ-ray emission region is at most the size of the binary
system. The companion star in this system is of the type O5III,
γ-ray emission alone. Electrons with energies
are
100 s. Therefore, the pulsar’s spindown power needs to be at least
10^{36} \text{erg s}^{-1} in order to provide the energy for the observed
γ-ray emission alone.

In the accretion scenario, a situation that is encountered in
microquasars, the stellar wind of the companion star is accreted
onto the compact object and gravitational potential energy is
released as radiation. The accretion luminosity of a neutron
star is
\begin{equation}
L_{\text{acc}} = \left( \frac{3}{10^{10} M_{\odot} \text{yr}^{-1}} \right) \left( \frac{M_{C}}{1.4 M_{\odot}} \right) \left( \frac{10 \text{ km}}{R_{\odot}} \right) \times 1.2 \times 10^{36} \text{erg s}^{-1},
\end{equation}
where \( M_{\odot} \) and \( R_{\odot} \) are the mass and radius of the compact object (Frank et al. 1992). \( M \) is the mass-accretion rate which
is of the order of \( 10^{-10} M_{\odot} \text{yr}^{-1} \) in a typical close binary system
with accretion of the stellar wind. Accretion can power the
observed γ-ray emission provided that the conversion efficiency
from accretion power to γ rays approaches unity. Much higher
mass-accretion rates and thus a higher accretion luminosity can
be achieved by Roche lobe overflow, for instance an accretion
rate of \( 10^{-4} M_{\odot} \text{yr}^{-1} \) is discussed for SS 443 in such a scenario
(for a review see Fabrika 2004). A more massive compact object
can also increase the accretion luminosity by a factor of a few.

The peak of the VHE emission at phases between 0.2 and 0.4
coincides with the decline of the HE γ-ray emission towards its
broad minimum between orbital phases 0.3 and 0.7 (see Fig. 1).

### 3. Discussion

The emission from HESS J0536–675 is variable and modulated
with the orbital period of the binary system, indicating that the
size of the γ-ray emission region is at most the size of the binary
system. The companion star in this system is of the type OSIII,
with a typical mass of 40 \( M_{\odot} \) (Martins et al. 2005). For a neutron
star with a mass of 1.4 \( M_{\odot} \), the compact object the semi-major
axis of the orbit would be 0.32 AU.

The two scenarios proposed for γ-ray binaries are that the
γ-ray emission can be powered either by the spin-down of a pul-
sar or by accretion of the stellar wind onto the compact object. In
the pulsar wind scenario, electrons are accelerated in the vici-
inity of the pulsar or in the shock front between the pulsar wind and
stellar wind. The relativistic electrons produce γ-ray emission by
inverse Compton (IC) upscattering of stellar photons. A typical
OSIII star has a surface temperature of 40 kK and a luminosity of
5.4 \times 10^3 \( L_{\odot} \) (Martins et al. 2005). The IC scattering is in
the Klein–Nishina regime and a hard electron spectrum with an
index of \(-1.5\) is required to produce the observed γ-ray spec-
trum. For a binary separation of 0.32 AU the stellar photon field
has an energy density of 253 \text{erg cm}^{-3}. Electrons with energies
between 0.5 and 50 \text{TeV} and a total energy of \( 2.5 \times 10^{36} \text{erg} \) are
required to produce the observed γ-ray emission. The IC cooling
time (Khangulyan et al. 2008, Eq. (1)) of TeV electrons in this
photon field is of the order of 100 s. Therefore, the pulsar’s spindown
power needs to be at least \( 10^{36} \text{erg s}^{-1} \) in order to provide the
energy for the observed HE γ-ray emission alone.

Notes. The on-peak region covers orbital phases from 0.2 to 0.4, the off-peak region the orbital phases from 0.4 to 1.2. Orbital phase zero is at the maximum of the HE γ-ray emission (MJD 57 410.25).

### Table 1. Statistical results and spectral parameters for different orbital phase bins of HESS J0536–675.

<table>
<thead>
<tr>
<th>Orbital phase bin</th>
<th>Excess</th>
<th>Significance</th>
<th>( \Phi_{1\text{TeV}} \times 10^{-13} \text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1} )</th>
<th>( \Gamma )</th>
<th>( F(&gt;1 \text{TeV}) \times 10^{-13} \text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1} )</th>
<th>( L(1\text{–}10 \text{TeV}, 50 \text{kpc}) \times 10^{35} \text{erg s}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full orbit</td>
<td>76.3</td>
<td>6.4 ( \sigma )</td>
<td>2.0 \pm 0.4</td>
<td>2.5 \pm 0.2</td>
<td>1.4 \pm 0.4</td>
<td>1.4 \pm 0.2</td>
</tr>
<tr>
<td>On-peak</td>
<td>41.1</td>
<td>7.1 ( \sigma )</td>
<td>5 \pm 1</td>
<td>2.1 \pm 0.2</td>
<td>5 \pm 2</td>
<td>5 \pm 1</td>
</tr>
<tr>
<td>Off-peak</td>
<td>35.0</td>
<td>3.3 ( \sigma )</td>
<td>–</td>
<td>2.4 (fixed)</td>
<td>&lt;0.88 (95% CL)</td>
<td>&lt;0.88 (95% CL)</td>
</tr>
</tbody>
</table>

H.E.S.S. Collaboration: Detection of variable VHE γ-ray emission from the extra-galactic γ-ray binary LMC P3
HE and VHE emission from LMC P3 helps to fill the zoo of γ-ray binaries and will help to understand the underlying particle acceleration and γ-ray production mechanisms. Detailed modelling of the HE and VHE light curves requires knowledge of the orbital parameters of the system.

The sensitivity of H.E.S.S. only allows the detection of VHE γ-ray radiation during the high-state of the emission. The 3.3 σ statistical significance during the off-peak part of the orbit may indicate that the VHE emission extends into this part of the orbit as well. The ten-fold sensitivity of the future Cherenkov Telescope Array (CTA; Hinton et al. 2013) will allow for the investigation of this part of the orbit of the binary system.

4. Conclusions

Variable VHE γ-ray emission from the newly discovered binary system LMC P3 has been detected with H.E.S.S. The emission is phase-locked to the orbital period of the system. This makes HESS J0536–675 the sixth VHE γ-ray-emitting binary and the first extra-galactic γ-ray binary. The energy spectrum of the VHE γ-ray emission is described by a simple power law. The orbit-averaged VHE luminosity of the system is $(1.4 \pm 0.2) \times 10^{33} \text{erg s}^{-1}$. During 20% of the orbit the VHE luminosity reaches $(5 \pm 1) \times 10^{33} \text{erg s}^{-1}$. This makes HESS J0536–675 the most luminous γ-ray binary known to date. The VHE γ-ray emission can be either powered by the spin-down of a pulsar or by accretion of the stellar wind onto the compact object. A luminous pulsar ($\dot{E} \geq 10^{36} \text{erg s}^{-1}$), a high mass-accretion rate or a very massive compact object are needed to provide the energy for the observed VHE γ-ray emission. The VHE emission is out of phase with the HE emission which may be explained by absorption due to pair production, or by different particle distributions responsible for the HE and VHE γ-ray production. Observations with CTA may lead to detection of γ-ray emission during the off-peak part of the orbit allowing the modelling of the entire light curve.

Acknowledgements. The support of the Namibian authorities and of the University of Namibia in facilitating the construction and operation of H.E.S.S. is gratefully acknowledged, as is the support by the German Ministry for Education and Research (BMBF), the Max Planck Society, the German Research Foundation (DFG), the Alexander von Humboldt Foundation, the Deutsche Forschungsgemeinschaft, the French Ministry for Research, the CNRS-IN2P3 and the Astraparticle Interdisciplinary Programme of the CNRS, the U.K. Science and Technology Facilities Council (STFC), the IPNP of the Charles University, the Czech Science Foundation, the Polish National Science Centre, the South African Department of Science and Technology and National Research Foundation, the University of Namibia, the National Commission on Research, Science & Technology of Namibia (NCRST), the Innsbruck University, the Austrian Science Fund (FWF), and the Austrian Federal Ministry for Science, Research and Economy, the University of Adelaide and the Australian Research Council, the Japan Society for the Promotion of Science and by the University of Amsterdam. We appreciate the excellent work of the technical support staff in Berlin, Durham, Hamburg, Heidelberg, Palaiseau, Paris, Saclay, and in Namibia in the construction and operation of the equipment. This work benefited from services provided by the H.E.S.S. Virtual Organisation, supported by the national resource providers of the EGI Federation. We thank Robin Corbet for providing the HE light curve data shown in Fig. 1.

References

Ackermann, M., et al. (Fermi LAT Collaboration) 2012, Science, 335, 189