INAF – TIME ALLOCATION COMMITTEE

Application for observing time **Category: B**

Period AOT39 (April 2019 – September 2019) **Submit using: www.tng.iac.es/submit.html**

1. Title

REM monitoring of the Be/X-ray transient 1A 0538−66

2. Abstract

1A 0538−66 is a Be/X-ray transient containing a 69 ms X-ray pulsars, one of the fastest known in high-mass X-ray binaries. The source shows weak persistent emission and bright outbursts lasting from a few hours to two weeks. The peak luminosity reaches $\sim 10^{39}$ erg s^{-1} ($0.5-20$ keV), thus exceeding the isotropic Eddington limit. 1A 0538−66 is known to be variable in the optical domain and shows a strong correlation between the optical and X-ray fluxes. We propose to continue our daily monitoring of 1A 0538−66 with REM to catch the source during a bright optical flare which would indicate the onset of an X-ray outburst that can be followed with X-ray telescopes through a ToO request. In this respect, the REM observations would play a key role to trigger a XMM-Newton ToO observation that we have obtained. An X-ray observation of 1A 0538−66 during a bright state will shed a light on one of the most poorly known aspect of the accretion onto neutron stars. The stand-alone optical observation is relevant to improve our knowledge about the optical and X-ray evolution of 1A 0538−66. We will use the REM observations to further investigate the long-term and short-term variability recently observed by REM.

3a. Number of requested hours per telescope and instrument

TNG					REM	
DOLORES	DOLOR.+MOS	NICS	HARPS-N	GIANO-B	ROSS	REMIR
					29	42

3b. Observing modes

TNG:		Visitor		Service		ToO
REM:		Rapid Response	X	Queuing		ToO

4a. Preferred months

first choice: second choice:

4b. Other scheduling constraints (use also box 14)

daily monitoring

5a. Past and future of the project

a) Hours already awarded to the project: 160

b) Hours foreseen to complete the project: 0
(not including this request)

6. Principal investigator

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7. Co-investigators (name and institution)

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8. Status of the project

Telescope	Instrument	Date	Hours	Notes
REM	ROSS2	daily monitoring, from 2014.09.03 to 2019.03.31	0.16 per night	
REM	REMIR	daily monitoring, from 2014.09.03 to 2019.03.31	0.23 per night	

Description

Observations of 1A 0538−66 during AOT39 period, spanning six months, are needed to trigger the XMM-Newton observation obtained by our team (obsid: 07809301) and for the achievement of the other goals of the project (a description of the most relevant results are given in Section 10).

Publications

A paper based on the first year of observations of 1A 0538−66 with REM has been accepted for publication in A&A (Ducci L. et al. 2016, A&A 595, 103).

9a. If this proposal is a part of a PhD thesis, write here the name of the student, the thesis title and briefly describe the relevance of these observations for the thesis goals.

9b. Is this, or a similar application submitted to other time allocation committees (e.g. ESO, TNG-CAT, ITP)? If yes, please specify which and explain if and why the proposals should be considered complementary.

10. Description of the programme (max. 3 pages, including references, tables, and figures.)

A) Scientific rationale 1A 0538−66 is probably the best known and least understood Be/X-ray transient in the Large Magellanic Cloud. It hosts a neutron star (NS) with a pulse period of 69 ms (Skinner et al. 1982) and orbital period of ~ 16.6 d. The spectral type of the donor star varies from B2 III-IV during quiescent periods (X-ray 'off') to B8-9 I during outbursts (Alcock et al. 2001). 1A 0538−66 was discovered in 1977 by the *Ariel V* satellite (White & Carpenter 1978) during an X-ray outburst reaching a peak luminosity of 8.5×10^{38} erg s^{-1}. Other outbursts with a similar luminosity were subsequently observed. Using *Einstein*, Skinner et al. (1982) found a pulsation of ~ 69 ms during a super-Eddington outburst ($L_x = 8 \times 10^{38}\,\mathrm{erg\,s^{-1}}$); this is the only measurement of the pulse period of 1A 0538−66. *ROSAT*, *BeppoSAX*, *ASCA*, and *XMM-Newton* (Campana et al. 2002; Kretschmar et al. 2004) revealed outbursts with lower luminosities ($L_x \approx 10^{33} - 10^{37}\,\mathrm{erg\,s^{-1}}$). The outbursts of 1A 0538−66 display wide range of durations from a few hours to ~ 14 days. The high dynamical range, spanning 5 orders of magnitude, and the absence of pulsations during the outbursts with luminosity $L_x \leq 10^{38}$ erg s^{-1}, can be explained with the source going from the propeller state to the direct accretion. The change of the accretion regime depends on the amount of inflowing matter and on the magnetic field of the NS. Campana et al. (2002) found that the required magnetic field is $B \leq 2 \times 10^{11}$ G and the minimum X-ray luminosity of 1A 0538−66 produced by the direct accretion is $L_{min} = 7 \times 10^{37}$ erg s^{-1}.

1A 0538−66 shows peculiar properties also in the optical bands. The photometric lightcurve from 1915 to 1998 shows a high variability, with V magnitude ranging from 15 to 12 and with periodic ($P \approx 16.6$ d) bright and fast optical flares (up to $L_{\rm opt} \approx 3 \times 10^{38}\,\mathrm{erg\,s^{-1}}$; $\Delta t \approx 1-2$ d) in phase with the X-ray outbursts. (Alcock et al. 2001; McGowan & Charles 2003). The photometric monitoring reveals a long-term modulation at $P_{\rm long} = 420.8 \pm 0.8$ days (with a reddening at low fluxes). The periodic flaring activity is only seen at certain phases of the 421-d cycle, suggesting that the long-term modulation is related to variations in the Be star envelope. To our knowledge, this is the only high mass X-ray binary that shows fast optical flares, associated with X-ray activity, brighter than the donor star. Contrary to low-mass X-ray binaries, where reprocessing of X-rays into optical/UV photons dominates or is comparable with the optical emission of the relatively faint donor star, most of the optical emission of Be/X-ray binaries is expected to come from the bright massive donor star and its circumstellar disc. McGowan & Charles (2003) defined four states (see Fig. 1 and its caption for a description). In their model, the brightness of the source decreases (from the quiescent to active state) as a result of the formation of the equatorial disc of the Be star observed approximately edge-on. The photometric behaviour of the Be star in 1A 0538−66 shows a reddening as the source becomes fainter, in agreement with the formation of a circumstellar disc. The rise of the brightness from the active to quiescent state is caused by the depletion of the circumstellar disc. As the NS passes through this disc it accretes material leading to X-ray and optical outbursts. Maraschi et al. (1983) proposed that the optical outbursts are due to (1) X-ray reprocessing in the primary envelope, whose mass, however, must greatly exceed that of an ordinary Be envelope, or (2) to cooling of an expanding shell accelerated by the X-ray bursts. During inactive periods the rotational energy loss of the pulsar should give rise to synchrotron radiation from radio to IR frequencies.

Starting from September 2014, the REM telescope performs a daily monitoring of 1A 0538−66. We published the results related to the first year of observations in Ducci et al. (2016). Fig. 2 shows the g, r, i, z, J, H, K, REM lightcurves. We found that the REM light curves show fast flares lasting one or two days that repeat almost regularly every ~ 16.6 days, which is the orbital period of the neutron star. Such periodicity is clear in the lightcurve folded at the orbital period (Fig. 3). If the optical flares are powered by X-ray outbursts through photon reprocessing, the REM light curves indicate that 1A 0538−66 is still active in X-rays; bright X-ray flares ($L_{\rm x} \gtrsim 10^{37}\,\mathrm{erg\,s^{-1}}$) could be observable during the periastron passages. The REM light curves show a long-term variability that is especially pronounced in the g band and decreases with increasing wavelength until it no longer appears in the near-infrared light curves. On the basis of the current models, we interpret these observational results with a circumstellar disc around the Be star observed nearly edge-on during a partial depletion phase. The REM light curves also show short-term variability on timescales of ~ 1 day, which is possibly indicative of perturbations in the density distribution of the circumstellar disc caused by the tidal interaction with the NS.

B) Scientific aim We propose to continue the daily monitoring of 1A 0538−66 with REM during the AOT39 period. The main aim of our program is to improve our knowledge about the properties and nature of 1A 0538−66. The detection of bright optical flares ($V < 12$) during the active state will indicate the onset of a bright X-ray outburst ($L_{\rm x} > 10^{38}$ erg s^{-1}) that can be followed with XMM-Newton (proposal 07809301, PI: L. Ducci) and other X-ray telescopes through a ToO request. The REM daily monitoring will be extremely important to trigger the X-ray observation with the highest possible X-ray flux. REM observations coupled with X-ray observations will allow us to test the models of McGowan & Charles (2003), Maraschi et al. (1983), and eventually propose a new model. Maraschi et al. (1983) pointed out that the two mechanisms proposed by them could be distinguished by new, simultaneous optical and X-ray measurements. If the optical flares are caused by X-ray reprocessing in a quasi-static envelope, a close correspondance of the optical and X-ray light curve is expected. If the optical flares are caused by the radiative cooling of an expanding shell in which the onset of supercritical accretion injects energy impulsively, the optical maximum should be appreciably delayed with respect to the X-ray maximum and the optical decay may be independent of the X-ray decay. In recent REM and OGLE observations, the 421 d cycle disappeared and the long-term variations seem to occur on irregular timescales (Ducci et al. 2016; Schmidtke et al. 2014). Figure 4 shows the recent REM data (Ducci et al. in preparation).

We will also study the optical variability of an X-ray binary candidate in the same FOV, [HP99] 445, of the *ROSAT* catalogue of LMC (Haberl & Pietsch 1999). We will exploit the capabilities of the ROSS2 and REMIR cameras of REM telescope to reach the goals of our program through lightcurves and colour magnitude diagrams with unprecedented details for this source.

Figure 1: The V- (top panel) and R-band (bottom panel) lightcurves of 1A 0538−66 from MACHO project observations. McGowan & Charles (2003) defined the following activity states:
(i) active, in the 421-d cycle the source is only active (in X-rays) during the extended dip;
(ii) high, optical/X-ray outbursts or mini outbursts, with recurrence time of ∼16.6-d; these outbursts are constrained in 421-d phase to only occur during the active state;
(iii) low, times when outbursts should not be seen in the active state;
(iv) quiescent, times when only the naked B star should be seen in the 421-d cycle.
In the top panel are indicated the *(i) active*, *(ii) high*, *(iii) low*, and *(iv) quiescent* states (figure adapted from Alcock et al. 2001).
The model of McGowan & Charles (2003) is consistent with the presence of Balmer and He I emission with P Cygni profiles that indicate the presence of a circumstellar disc during the active state. During the quiescent state the spectrum does not show any Balmer emission: the circumstellar disc is absent. However, Smale et al. (1984) found evidence for weak Hβ and Hγ emissions during some observations of the quiescent states. During the low state, Smale et al. (1984) found Hβ and Hγ emission lines with inverted P Cygni profiles that vary. They suggested that this is caused by the infall of material.

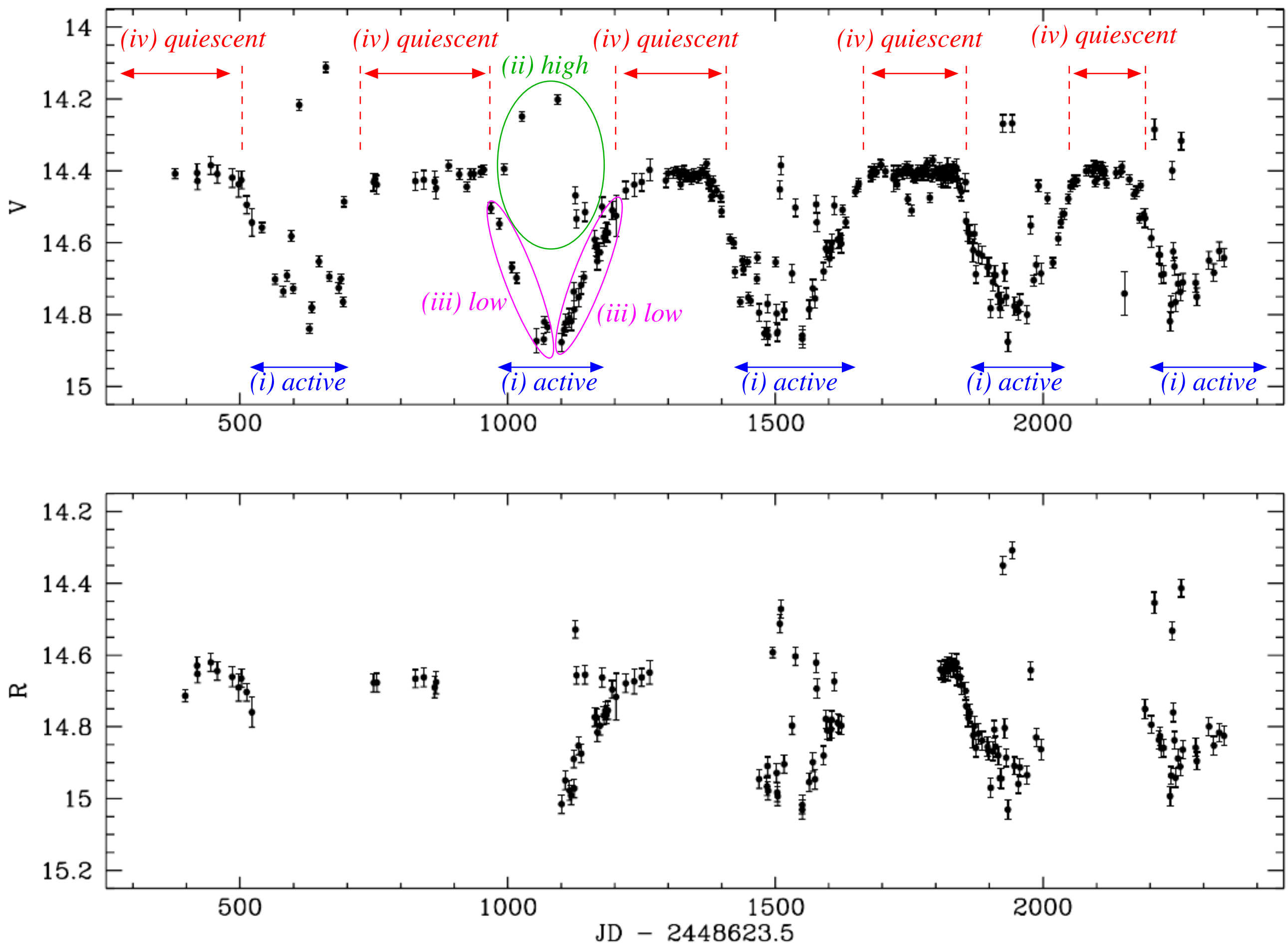
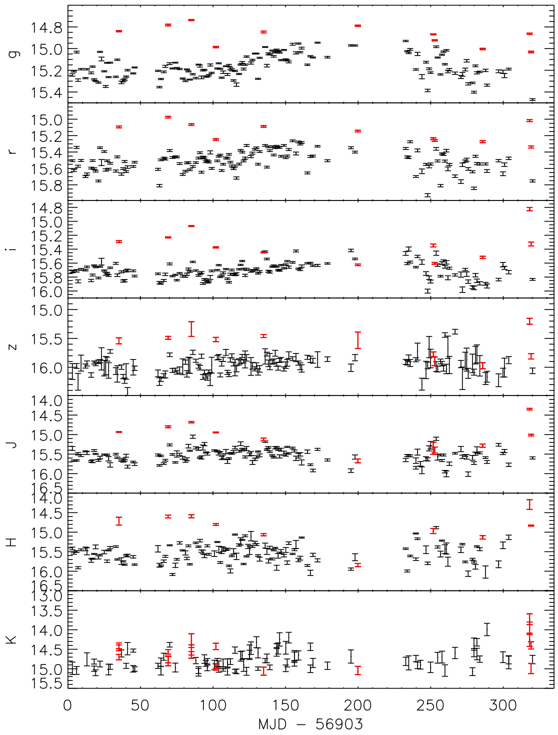


Figure 2: g, r, i, z, J, H, K, lightcurves of 1A 0538−66 observed with REM from $T_{\rm start} = 56903.2$ MJD (3 September 2014). Errors are indicated at the 68% confidence level.



References:

Skinner et al. 1982, Nature 297, 568
Alcock et al. 2001, MNRAS 321, 678
White & Carpenter 1978, MNRAS 183, 11
Campana et al. 2002, ApJ 580, 389
Mavromatakis & Haberl 1993, A&A 274, 304;
Campana 1997, A&A 320, 840
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Ducci et al. 2016 A&A 595, 103
Kretschmar et al. 2004, ESA-SP-552, 329
McGowan & Charles 2003, MNRAS 339, 748
Smale et al. 1984, MNRAS 210, 855
Maraschi, Traversini & Treves, 1983, MNRAS 204, 1179
Haberl & Pietsch, 1999, A&AS 139, 277
van Paradijs, 1998, ASIC, 515, 279, arXiv:9802177
Reig, 2011, Ap&SS 332, 1

Figure 3: g, r, i, z, J, H, K, lightcurves of 1A 0538−66 folded at $P_{\rm orb} = 16.646$ d ($T_0 = {\rm JD}244\,1443.1432$). Errors are indicated at the 68% confidence level. Second panel (from top) shows the detrended g-lightcurve obtained by subtracting the 5th order polynomial fitted to the g-lightcurve (excluding flares).

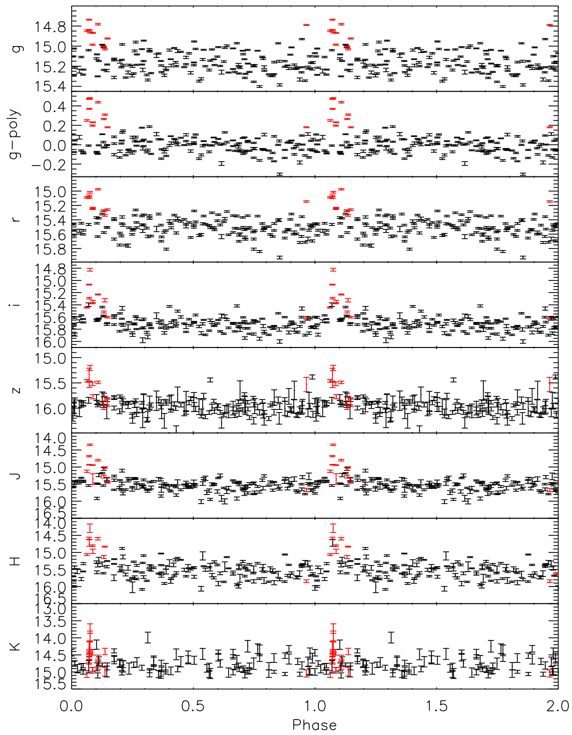
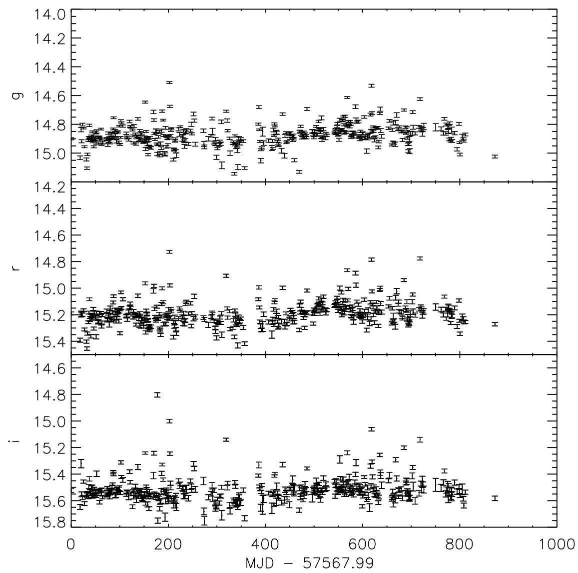


Figure 4: g, r, i, lightcurves of 1A 0538−66 observed with REM from $T_{\rm start} = 57567.99$ MJD (28 June 2016). Errors are indicated at the 68% confidence level.



11. List of targets (note that the absence of a proper object list and information may weaken the proposal)

Name	α	δ	Epoch	Mag.	Time	Additional Information
1A 0538−66	05 35 41.01	-66 51 53.5	J2000	V15	240000s	Visual magnitude variable from ~ 12 to ~ 15

12. Observational strategy and justification of requested time, including overheads.

We request the same observational strategy of the previous observations.
For the ROSS2 camera we ask for daily observations with exposure times described below, to get a S/N ≥ 20 for the g, r, i and z magnitudes. For the REMIR camera we ask for daily observations with exposure times described below, to get a S/N ≥ 10 for J, H, and K magnitudes. The observations can be divided in two OBs, each with associated optical (ROSS2) and infrared (REMIR) observations:

1.
   - $K_{\rm s}$: 3 dithers of 7 observations of $t_{\rm exp}$ =15 s; overheads: 57 s: [(15 s×7 + 57)×3 ≈486 s];
   - optical: 3 observations of $t_{\rm exp}$ =30 s; overheads 83 s: [(30 s + 83)×3 ≈339 s].
2.
   - J and H: 7 observations of $t_{\rm exp}$ =15 s overheads: 57 s: [(15 s×7 + 57)×2 ≈324 s];
   - optical: 2 observations of $t_{\rm exp}$ =30 s; overheads 83 s: [(30 s + 83)×2 ≈226 s].

13. Requested instrument(s) setup

Id	Instrument	Binning	Filter(s)	Slit	Grism	Time	Additional Information

14a. Moonlight constraints

Max. # of days from new moon

14b. Scheduling constraints, special requirements and other remarks
(please include justification of constraints in 14a)

Daily monitoring.

15. Observational background of the applicants

Name of the observer(s) at TNG:

Experience of the observer(s) with the requested TNG instrument(s)

Experience of the observer(s) with other telescopes/instruments
The proposing team includes people with specific experience on REM data analysis and has a long expertise in optical, X- and gamma-ray scientific data analysis.

FGG-INAF complies with the Spanish law for sensible data management (LOPD). Please read the page www.tng.iac.es/info/lopd/lopd-aot.html