Mem. S.A.It. Vol. 83, 251

Memorie della

Supergiant Fast X-ray Transients: an *INTEGRAL* view

P. Blay[1], I. Negueruela[2], and V. Reglero[1]

[1] Image Processing Laboratory University of Valencia PO BOX 22085, E-46071, Valencia, Spain, e-mail: pere.blay@uv.es

[2] DFISTS, EPSA, Universidad de Alicante, Apdo. 99, 03080 Alicante, Spain

Abstract. Supergiant Fast X-ray Transients have been recently unveiled as a new class of High Mass X-ray Binaries thanks to the excellent survey capabilities of the *INTEGRAL/IBIS* instrument. Although there is a general agreement on explaining the behavior of supergiant Fast X-ray Transients as the result of accretion by a compact object from the wind of a supergiant star, there are unsolved questions about the details on how the mass transfer takes place. We will review the peculiarities of these sources from the multiwavelength point of view.

Key words. Stars: binaries – Stars: early-type – Stars: mass-loss – Stars: winds, outflows – X-rays: binaries

1. Introduction

One of the *INTEGRAL* (INTErnational Gamma-Ray Laboratory, see Winkler et al. 2003) legacies is the unveiling of a new class of High Mass X-Ray Binary systems (HMXB), the class of supergiant Fast X-Ray Transients (SFXTs, Negueruela et al. 2006). What are SFXTs? On the one hand they are HMXBs with a supergiant companion, on the other hand they are Fast X-ray Transients (FXTs). We will review these two features in the next paragraphs.

Classical supergiant HMXB are binary systems composed by two stellar objects orbiting around each other. One of them is a supergiant OB star, the other is a compact object (neutron star or black hole). Supergiant stars are known to suffer great mass loss in the form of a stellar wind. The compact star can interact with material in this wind, which will free-fall onto it by gravitational attraction. About a half of the energy stored in the captured matter, will be released during the infall. The rest will be released when reaching the compact object surface (or event horizon). Only a very small fraction of the wind matter is captured by the compact object, therefore this accretion process is not very efficient. Typical X-ray luminosities for this class of HMXB are on the order of 10^{36} erg cm^{-2} s^{-1} (Nagase 1989). There exists also the possibility that the supergiant star and the compact companion are so close together that the former fills its Roche-Lobe, that is, it extends its surface beyond the point (the first Lagrangian point, L_1) at which the gravitational potential of both components of the binary system compensate. In this case surface matter of the supergiant will free-fall onto the

Send offprint requests to: P. Blay

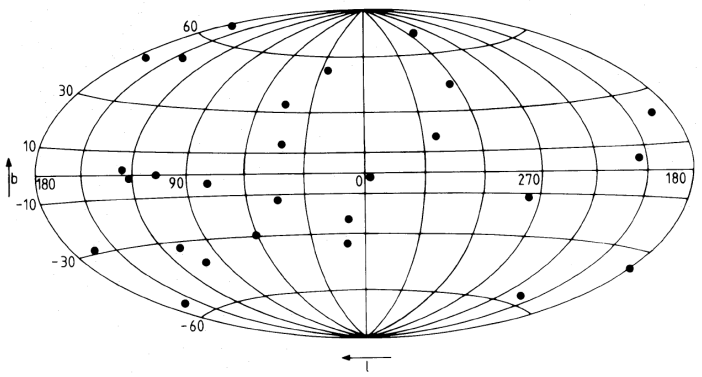

Fig. 1. Map of the location of detected FXTs by *Ariel V* in galactic coordinates, showing the galactic and extragalactic nature of these detections. Reproduced by permission of John Wiley Sons Ltd., originally published in Pye & McHardy (1983).

compact companion by overflowing at L_1. It is very likely that an accretion disc is formed as matter spirals inwards. This kind of accretion is more efficient than wind capture, as a large amount of matter is accreted, and typical X-ray luminosities of this class of HMXB are on the order of 10^{38} erg cm^{-2} s^{-1} (Nagase 1989).

In both scenarios, the compact companion can be considered point-alike when compared to its massive counterpart. This approximation is important, as it is an indication that X-ray emission will trace the position of a point-like source immerse in the neighborhood of the supergiant star, and, therefore, will probe with high accuracy the local physical conditions.

FXTs were already known before the *INTEGRAL* era. An interesting fauna of galactic and extragalactic sources can show this behavior (Pye & McHardy 1983). FXTs are characterized by fast increases of flux, of several orders of magnitude and lasting from minutes up to a few hours, over their quiescence level, generally with a steeper rise and a slower decay (Heise & int Zand 2004). Figure 1 shows a plot from Pye & McHardy (1983) which shows the location of FXTs detected by *Ariel V*. Heise & int Zand (2004) analyze FXT data from the Wide Field Cameras (WFCs) on *BeppoSax* and find that, from a total of 49 sources, 19 could be identified with galactic objects. Figure 2 shows one of this FXTs as observed by *RXTE/ASM*, namely XTE J1739-302, despite its large field of view, the sensitivity of *RXTE/ASM* is limited for the purpose of studying FXTs.

Sguera et al. (2005) analyzed *INTEGRAL* data of several FXTs. Motivated by this work, Negueruela et al. (2006) analyzed several FXTs with supergiant counterparts and proposed, because of their similar behavior and constituents, the grouping of these sources into a new class which they called SFXT. It is important to emphasize the multi-wavelength nature of the definition of this new class of sources. Not only through the characterization of high energy emission, but also thanks to the laborious task of identification of counterparts, with IR/optical facilities, a complete classification of a given source can be performed. Only at the end of the whole process we can confirm or discard the association of the source to the SFXT class.

What has been the role of *INTEGRAL* in the definition of the new class? The *IBIS/ISGRI* detector, part of the *INTEGRAL* payload, is an excellent survey instrument. Because of its large field of view (19x19°) and sensitivity, it has proved to be very good to detect transient sources. Pointing instruments, with much narrower fields of view, will miss transient events unless they happen right in the pointing direction, which is very unlikely to occur. The very good performances of the *ISGRI* detector led

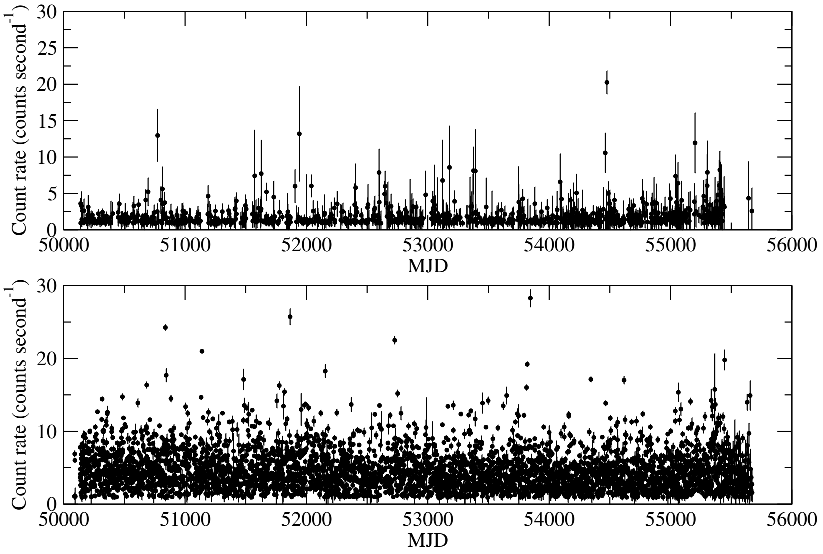

Fig. 2. **Top:***RXTE/ASM* 2-12 keV light curve of the FXT XTE J1739-302. **Bottom:** *RXTE/ASM* 2-12 keV light curve of the supergiant HMXB Vela X-1.

to the above mentioned work of Sguera et al. (2005) on FXTs. Figure 3 shows an *ISGRI* light curve, in the 20–40 keV energy range, of the SFXT XTE J1739-302 (see also Blay et al. 2008). The long term light curve is very useful to compare epochs of activity and quiescence. Whenever the *INTEGRAL/IBIS* instrument had the source in the filed of view but it was not detected it is indicated in Figure 3 with a blue square. Blue squares, then, will be indicative of periods of quiescence. It is noticeable how some of the outburst rise several orders of magnitude preceded and followed by quiescence periods. This is the typical behavior of SFXTs. The more detailed view of the light curve in the right panel of Figure 3 shows the fine flaring structure of the outburst, also a typical feature of SFXTs.

A list of confirmed SFXTs is shown in Table 1. The very short orbital periods of IGR J16479-4514 and IGR J17544-2619 represent a challenge to the modeling of these sources. There is a possible identification of AX J1841.0-0536 with the high energy source HESS J1841-055V (see Sguera et al. 2009).

Table 1. List of confirmed SFXTs together with the spectral types of their supergiant companions and the orbital period in case it is known.

System	Spectral Type	P_{orb} (d)
IGR J11215-5952	B1Ia	165
IGR J08408-4503	O8.5Ib(f)	35?
IGR J16465-4507	O9.5Ia	30.3
IGR J16479-4514	O9.5Iab	3.2
XTE J1739-302	O8.5Iab	51.5?/12.9?
IGR J17544-2619	O9Ib	4.9
SAX J1818.6-1703	B0I	30?
AX J1841.0-0536	B0.2Ibp	
AX J1845.0-0433	O9.5Ia	
IGR J18483-0311	B0.5-B1 Iab	18.25

Figure 2 compares the RXTE/ASM light curves of the SFXT XTE J1739-302 with that of the classical supergiant HMXB Vela X-1. A priory there are some similarities, only a closer look to the structure of the outbursts would show up the difference. We can notice,

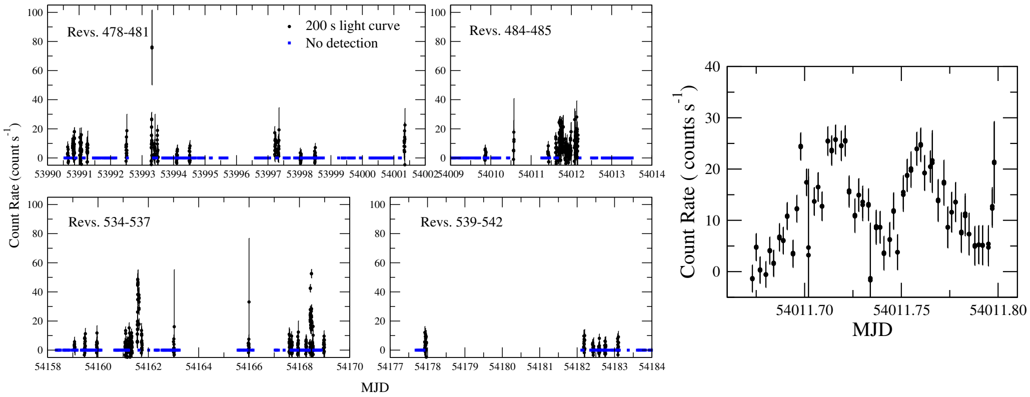

Fig. 3. Left: *INGTEGRAL/IBIS* 20-40 keV light curve of the SFXT XTE J1739-302. **Right:** Detailed view of a 200s binned light curve of XTE J1739-302 where the typical flaring structure of SFXTs outburst is shown. For more details see Blay et al. (2008) and Martínez-Núñez et al. (2010)

however that some classical supergiant wind-fed systems, like Vela X-1, sometimes show fast outbursts which mimic the FXTs behavior (Negueruela et al. 2007).

The observation of the optical counterparts to SFXTs is asimportant as the follow-up in X and γ-ray bands. Optical, IR and UV observations can be a key to understanding the behavior of SFXTs and how much they differ from classical wind-fed HMXB.

2. High energies, or how the compact companion interacts with the stellar wind

Orbital parameters of several classical supergiant HMXB with accretion fed by wind capture are shown in Table 2. We notice that, in terms of the supergiant stellar radius, all neutron stars belonging to these systems have orbits within $2R_{\star}$.

In the mid-80s (see Moffat 2008) observational evidence was collected regarding the presence of some kind of granulation in stellar winds. The more direct evidence came from observation of the evolution of subpeaks in time series of spectroscopic observations of emission lines in Wolf-Rayet (WR) stars (Moffat 2008). These structures were clearly due to small-scale wind perturbations and were universal in, at least, strong WR winds (see Schumann & Seggewiss 1975).

The winds in supergiant early-type stars are radiatively driven. This process is unstable and will lead to formation of inhomogeneities and structures (clumps). The *clumping factor* relates the density of the clump with the mean surrounding density and it is predicted to grow with distance (i.e. further away from the star the wind material is increasingly more concentrated in clumps). Close to the supergiant ($<2R_{\star}$) the number of clumps will be high enough as to be seen as inhomogeneities in a dense stellar wind media. For this reason, X-ray luminosity due to wind accretion in classical supergiant HMXB is highly variable and moderately intense. The compact companion in this case is immerse in a region of high clumping density (lower clumping factor). If we move further away from the supergiant, the clumping factor increases, implying that clumps are farther away from each other, and the probability of the compact object to find a clump in its orbit is decreased. In this case we observe quiescence epochs followed by rapid increases of luminosity when the compact object accretes matter from a clump. The clump density and size needed to match the observed X-ray luminosities and flare durations of SFXTs fits well within the general limits derived from theoretical models (see Negueruela 2010 and Walter, Zurita-Heras, & Leyder 2008).

Table 2. Geometrical parameters for the orbits of wind-fed classical supergiant HMXBs with well known orbital solution.

System	P_{orb} (d)	Spectral Type	supergiant Stellar Radius ($R_\odot$)	Semi-major axis ($R_\star$)
4U 1700-37	O6.5Iaf	3.4	22	1.4
4U 1538-52	BOI	3.7	17	1.7
4U 1907+09	O8-O9Ia	8.4	26	2.0
Vela X-1	B0Iab	8.9	28	1.9
2S 0114-65	B1Ia	11.8	35	1.6
1E 1145.1-6141	B2Ia	14.4	40	2

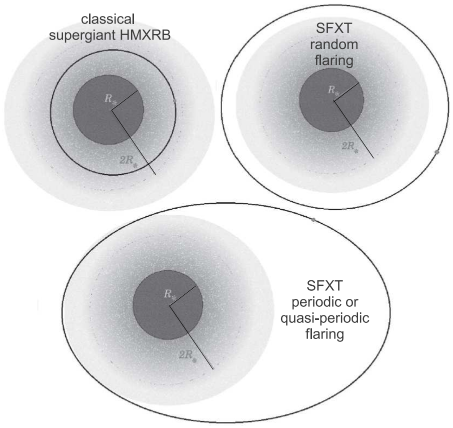

Fig. 4. Schematic view which shows how the observed behaviors of classical supergiant HMXBs and SFXTs can be explained with the clumpy wind assumption and by invoking different orbital configurations.

Within this framework, by invoking a wide range of orbital geometries, both the behavior of classical supergiant HMXB and SFXTs can be explained (see Figure 4). Therefore, this picture would naturally extend what we know about HMXB to the newly define class of SFXTs.

An alternative explanation was proposed by (Sidoli et al. 2007), assuming the hypothetical presence of a denser equatorial wind in the supergiant star . This model was proposed for the SFXT IGR J11215-5952, which shows periodic X-ray outbursts, and its application to other systems is not straightforward. Moreover, it requires the formation of a dense equatorial region, which has not been detected yet in any OB supergiant.

Grebenev & Sunyaev (2007) and Bozzo, Falanga & Stella (2008) invoke properties of the spinning compact companion to explain the observed x-ray behavior. Gated mechanisms to allow or inhibit accretion by interaction of matter with the magnetic field of the compact companion are invoked. These will surely be complementary to the other scenarios. An important theoretical effort by Ducci et al. (2010) tries to link all these scenarios (equatorial denser wind, clumpy structure and gated mechanisms) to explain the observed behavior of SFXTs.

Whatever the final explanation, it is clear that SFXTs are extreme objects and therefore they are very good candidates to explore the theories of wind structure, binary orbit evolution, and accretion onto compact objects.

3. IR/Optical, or the quest for the massive counterpart

Left panel of Figure 5 (extracted from Reig et al. 2005) shows the *ISGRI* location error of a HMXB. The advantage of using a pointing instrument is great, as the error box is smaller and the number of candidates is greatly reduced. In order to select the right candidate, there are two possible procedures:

– *Photometric method:* A photometric color suitable to measure an observable characteristic of OB supergiants (like, for example,the Hα line in emission) can be chosen and then a photometric survey of the

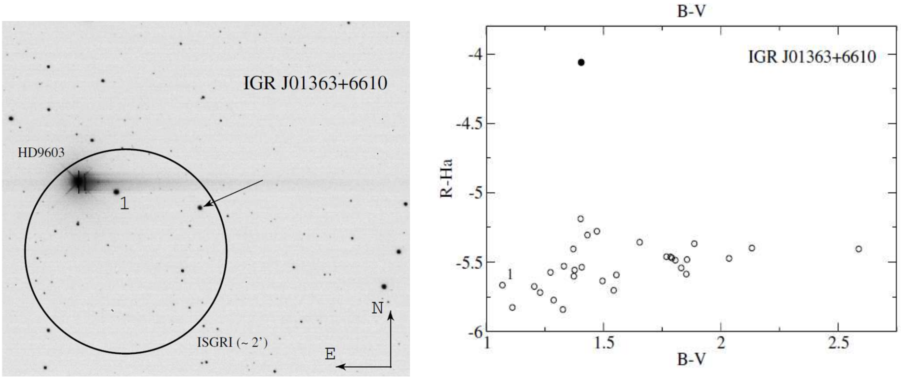

Fig. 5. Photometric colors used to identify the optical counterpart to IGR J01363+6610. Credit: Reig et al., A&A, 440, 637, 2005, reproduced with permission ESO.

area of interest is performed. Right panel of Figure 5 shows how from all the candidates within an error box, and by using the photometric filter R_α and the photometric color *(B-V)*, built with Johnson B and V filters, only one candidate arises as potential counterpart to the system, as it is the only one in the area showing emission in the H_α line (plot from Reig et al. 2005). It is interesting to notice that IR wavelengths are sometimes more suitable for this task, specially when the candidate can be obscured by interstellar or neighboring matter.

– *Spectroscopic method:* A second choice is to perform spectroscopy of all stars in the area of interest and select possible candidates from its spectral properties. Figure 6 (from Negueruela et al. 2006) shows H_α in emission for the selected candidate for the optical counterpart to XTE J1739-302. Not only H_α line is emission but it also shows variability typical of HMXBs. See also Masetti et al. (2006) for a review on optical identifications of counterparts to HMXBs.

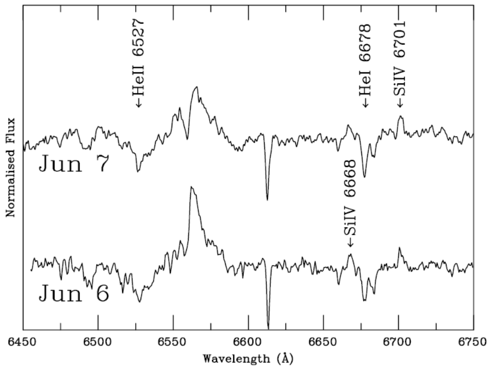

Fig. 6. Medium resolution H_α spectroscopy of the candidate optical counterpart to XTE J1739-302. Reproduced by permission of the AAS, originally published in Negueruela et al. (2006), ApJ, 638, 982.

Once the candidates are selected, the next step is their spectral classification, usually by comparison to standard stars (see, for example, Negueruela et al. 2006 and Pelliza, Chaty & Negueruela 2006). Because of the obscured nature of some of these systems, IR spectral classification, although less precise, is of great interest (see, for example Negueruela et al. 2006b and Nespoli, Fabregat & Mennickent 2008).

4. UV: wind formation and X-rays diagnostics

Ultra-Violet radiation drives the wind, but at the same time the atomic species involved are sensitive to X-ray radiation pressure (photoionitzation), therefore UV bands are not only useful to characterize the source but also to investigate the effects of the presence of an X-ray emitter (as it is the compact companion to the SFXT). Previous work has only been done only in more luminous (10^{35}–10^{36} erg s^{-1}) supergiant HMXBs (see, for example can Loon et al. 2001). However model predictions indicate that effects can be visible from luminosities as low as 10^{33} erg s^{-1} (Blondin 1994).

Ducci et al. (2010) analyze the X-ray photoionitzation effect in the wind media of SFXTs and reach the conclusion that it can negligible for longer orbital periods (>15 d) but will have observable consequences for shorter orbital periods (<15 d), though so far this is only a theoretical prediction.

Furthermore, UV wavebands can help to improve considerably the spectral classification of the supergiant companion and help to resolve the peculiarities of the local environment with the aid of the UV absorption band at 2200 Angstroms.

5. Conclusions

To favor or disfavor proposed models to explain the SFXT behavior, we need to solve for orbital motions and compare different orbit geometries (radial velocities, pulse delay analysis, etc). Therefore, a multifrequency approximation becomes mandatory. Same emphasis must be put into the characterization of the supergiant as is being put in the high energy characterization of the source. Some possible ways of action could be:

- Seek for UVBRI photometric modulation: small amplitude photometric variations can reveal important facts about the behavior of the supergiant surface (presence of stellar pulsations, for example) and periodic or quasi-periodic modulations in the neighboring matter, modulated with the rotational period of the supergiant star.
- Optical/IR spectral evolution and morphology: mass loss and propertied of the circunstellar matter can be traced with time series of medium to hight resolution spectroscopy of selected optical lines. IR spectroscopy is specially relevant to follow up the behavior of the supergiant star when it is obscured by interstellar absorption.
- UV photometric and spectroscopic characterization (with HST and the incoming WSO-UV): we have already mentioned the relevant role of the UV bands in the analysis of the wind structure of supergiant stars and the effects of X-ray photoionitzation.
- SFXTs in other galaxies (LMC and SMC): the identification and follow up of SFTXTs in LMC or SMC would offer the possibility to study a sample of sources at a similar distance and in an environment which differs from the local conditions in the Milky-way.

On going X-ray and γ-ray characterization of quiescent and flaring states and spectral characterization are leading to interesting results on SFXTs, but only a complete multiwavelength approach will help to explain the SFXT behavior and their link to the classical supergiant HMXBs.

6. Discussion

VALENTÍ BOSCH-RAMOÓN: Within the wind clumping framework, and between micro-clumping and macro-clumping, which one is used to model the behaviour of SFXTs?

PERE BLAY: The scenario propossed to explain the behaviour of SFXTs and classical supergiant HMXBs makes use the idea of macro-clamping. However, to my knowdeledge, efforts are being put in testing how microclumping fits in the SFXT and HMXBs scenarios.

Acknowledgements. Pere Blay acknowledges support from the Spanish Ministerio de Ciencia e Innovación through project 20100026-ASIM.

References

Blay, P., et al., 2008, A&A 489, 669
Blondin, J.M., 1994, ApJ, 435, 756
Bozzo, E., Falanga, M., & Stella, L., 2008, ApJ, 683.1031
Ducci et al. 2010, MNRAS, 1365
Heise, J, & and int Zand, J., 2004, Nuclear Physics B, 132, 263

Grebenev, S.A., & Sunyaev, R.A., 2007, Ast. Lett., 33, 149

Martínez-Núñez, S., et al. 2010, ASPC, 422, 253

Masetti, N., et al., 2006, A&A 449, 1139

Moffat, F.J., 2008, *Clumping in Hot Star Winds*, W.-R. Hamman, A. Feldmeier, & L. Oskinova eds, Postdam: Univ.-Verl., 17

Nagase, F, 1989, PASP, 41,1

Negueruela, I., Smith, D. M., Reig, P., Chaty, S., & Torrejn, J. M., 2006, Proceedings of the The X-ray Universe 2005, ESA SP-604, 165

Negueruela, I., Smith, D. M., Harrison, T. E., & Torrejn, J. M., 2006, ApJ 638, 982

Negueruela, I., Smith, D. M., Torrejn, J. M., & Reig, P., 2007, The Obscured Universe. Proceedings of the VI INTEGRAL Workshop, ESA SP-622, 255

Negueruela, I, 2010, ASPC, 422, 57

Nespoli E., Fabregat, J., & Mennickent, R. E., 2008, A&A 486, 911

Pellizza, L. J., Chaty, S., & Negueruela, I., 2006, A&A, 455, 653

Pye, J. P., & McHardy, I. M., 1983, MNRAS, 205, 975

Reig, P., et al. 2005, A&A 440, 637

Schumann, J. D., & Seggewiss, W., 1975, IAUS, 67, 299

Sguera, V., et al. 2005, A&A, 444, 221

Sguera, V., et al. 2009, ApJ, 697, 1194

Sidoli, L., Romano, P., Mereghetti S., 2007, A&A 476, 1307

van Loon, J. Th., L. Kaper, L., & Hammerschlag-Hensberge, G., 2001, A&A 375, 498

Winkler, C., et al. 2003, A&A, 411, L1

Walter, R., Zurita-Heras, J., & Leyder, J.C., 2008, *Clumping in Hot Star Winds*, W.-R. Hamman, A. Feldmeier, & L. Oskinova eds, Postdam: Univ.-Verl., 221