MODELLING THE NON-THERMAL EMISSION FROM BOW SHOCKS PRODUCED BY RUNAWAY STARS

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Abstract

Runaway O- and early B-type stars passing throughout the interstellar medium at supersonic velocities and characterized by strong stellar winds, can produce bow shocks that can serve as particle acceleration sites. Previous theoretical models predict the production of high energy photons by non-thermal radiative processes, but their efficiency is still debated. We present a new insight in the non-thermal emission treatment by introducing new approaches, new formulae and explaining the procedures we follow in our computations, and we also test its feasibility. We applied our model to AE Aurigae, the first reported star with an X-ray detected bow shock (López-Santiago et al. 2012), and BD+43 3654, in which the observations failed in detecting high-energy emission. From our analysis, we confirm that the X-ray emission from the bow shock produced by AE Aurigae can be explained by Inverse Compton (IC) processes involving the infrared photons of the heated dust. We also predict low high-energy flux emission from the bow shock produced by BD+43 3654, therefore in agreement with its non detection in X-rays (Terada et al. 2012).

AE Aurigae

Parameters	AE Aurigae	BD+43 3654
Wind mass loss rate	$10^{-7} M_{\odot}\ yr^{-1}$	$10^{-5} M_{\odot}\ yr^{-1}$
Wind velocity	1500 km s^{-1}	2300 km s^{-1}
Standoff radius	0.082 pc	1.8 pc
Luminosity of the star	$0.7 \times 10^5 L_{\odot}$	$9.7 \times 10^5 L_{\odot}$
Stellar temperature	32 kK	39 kK
Stellar radius	8.9 $R_{\odot}$	19.4 $R_{\odot}$
Ambient medium density	2.3 cm^{-3}	85 cm^{-3}
Stellar velocity	150 km s^{-1}	66 km s^{-1}
Distance	550 pc	1450 pc
Shock width	0.4 R_0	0.05 R_0
Bow shock lifetime	2.5 Myr	1.6 Myr

Table-1. Physical parameters of AE Aurigae and BD+43 3654

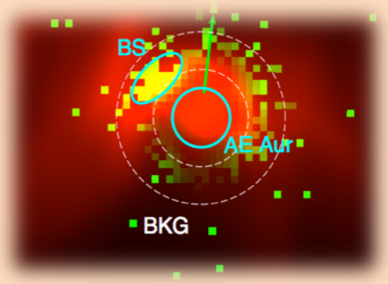

Fig.-1: WISE 12 μm in red and PN median photon energy map in the 0.3 – 8 keV band in green. The PN median photon energy of the BS region is higher than the PN median energy photon of the star, and is also associated with the infrared bow shock.

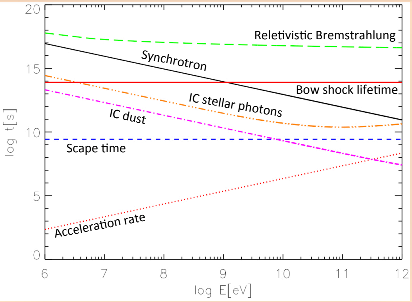

Fig.-2: Cooling time rates. The most efficient cooling process is the IC from dust photons. The maximum energy of electrons is 4×10^{11} eV, which is given by the point where the IC of the dust equals the acceleration rate.

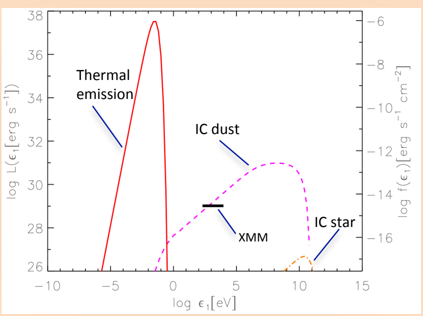

Fig.-3: Non-thermal luminosities computed for AE Aurigae. We also include the XMM-Newton detection limit for 50 ksec in the 0.3-10 keV band (black horizontal line).

AE Aurigae (see parameters in Table 1) was ejected at high velocity from its birth place in the Orion nebula cluster around 2.5 Myr ago as a result of the encounter of two massive binary systems. The later interaction with the IC 405 nebula resulted in the production of a bow shock (see Fig. 1). In Pereira et al. (in prep.) we consider for the first time the age of the bow shock and its effects on the energy and luminosity distributions. Only those electrons whose cooling time rate due to the different processes considered is smaller than the bow shock age, can effectively contribute to the non-thermal emission. In this case, only electrons with energies over 9×10^9 eV can produce synchrotron radiation, but the resulting low density of synchrotron electrons causes this process to be negligible. Electrons cannot cool down due to relativistic Bremstrahlung because the time rates for this process and for all energies are greater than the bow shock lifetime (see Fig 2). However, the Inverse Compton of both the infrared and stellar photons can explain the non-thermal X-ray emission detected with XMM (Figs. 1 and 3). The integrated flux in the 0.3 – 10 keV band is over 2×10^{-14} erg s^{-1} cm^{-2}, detectable with XMM-Newton.

BD+43 3654

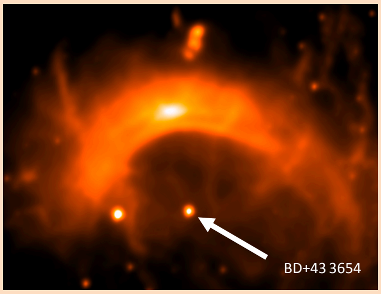

Fig.-4: WISE 12 μm of the bow shock formed by the star BD+43°3654. The heated shocked dust covers a wide range of the field, while the apex of the bow shock, where the particle acceleration region lies, is the small hottest region.

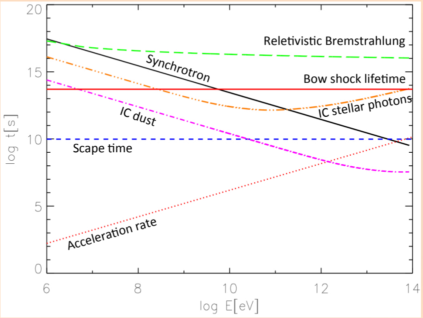

Fig.-5: Cooling time rates. Again, the Inverse Compton of the dust photons dominates over the non-thermal processes, giving a maximum energy of about 10^{12} eV. The minimum energy is now given by the time the cooling time rates are equal to the bow shock lifetime.

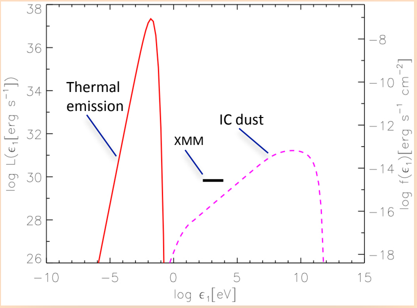

Fig.-6: Luminosity computations for BD+43 3654. Now the bow shock width considered is 0.09 pc. We also include the XMM-Newton detection limit for 50 ksec in the 0.3-10 keV band (black horizontal line).

The non-thermal luminosity computed for BD+43 3654 (see Fig. 4 and parameters in Table 1) explains the non X-ray detection of the bow shock by Terada et al. The integrated flux obtained in this case is 2×10^{-15} erg s^{-1} cm^{-2}, under the detection limit of XMM. The synchrotron emission is again neglected compared to the IC of the infrared photons (see Fig. 5). IC of the stellar photons is not either strong enough to be detected in an observation (see Fig. 6). However, in our computations, we consider that the width of the non-thermal emitting region of the O4 I star BD+43 3654 is three times the width of the region considered for AE Aurigae. The luminosity obtained is higher than the computed for AE Aurigae. The distance to the star, 1450 pc, is a major parameter to also explain the non-detection.

References

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- Longair, M. S. 2011, High Energy Astrophysics
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- Pereira et al., in prep.

Acknowledgements

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Conclusions: the consideration of the bow shock lifetime acts as a filter of the processes that can produce non-thermal emission, and thus has a major influence in the luminosity distribution. On the other hand, even very luminous bow shocks can not be detected in X-rays for distances over 1 kpc, restricting the high energy bow shock search to our neighbourhood.