Chapter 7

Conclusions : Lessons learnt regarding collimation in GRB afterglows

The main purpose of this study is to investigate the signature of collimation of GRB outflows. Much of the evidence for collimation of GRB outflows relies on the change of slope in light curves at different wavebands. We have therefore performed optical and radio observations of several GRB afterglows which we present in this thesis. In order to include the X-ray waveband in multiwavelength coverage, we have also analysed archival X-ray data of these afterglows, wherever available. By modelling these multiwavelength observations, we have been able to draw interesting conclusions not only about the outflow collimation, but also about the circumburst medium in several of these cases. In this chapter we highlight some of the interesting conclusions drawn in this thesis.

One of the most important cases we have presented is that of GRB 030329. The afterglow of this GRB has been one of the brightest till date. This afterglow is detectable at radio frequencies even today, more than four years after the explosion. This has made it possible for us to conduct a prolonged and detailed study of the evolution of the GRB fireball deep into the non-relativistic phase, thereby allowing us to test the predictions of the standard model of GRB afterglows.

One of the surprises from these observations has been that the amount of kinetic energy in the explosion, estimated from the non-relativistic regime, works out to be several times larger than the same estimated from the relativistic phase of the evolution ($\sim 8\times10^{50}$ erg vs $\sim 10^{50}$ erg). We recall that the estimate made during the relativistic phase includes corrections for the anisotropy of the outflow, which is assumed to be jet-like. In the non-relativistic phase, however, the outflow as well as the radiation is commonly assumed to be isotropic, and hence no such correction is made. This assumption may turn out to be too simplistic. The discrepancy between the two energy estimates mentioned above may indicate that there is some residual anisotropy in the radiation pattern and/or the outflow velocity even in the non-relativistic phase.

The outflow from GRBs is thought to start out as two counter-propagating jets. While the jets are still relativistic, the radiation received mainly comes from the jet propagating towards the observer. When the propagation becomes non-relativistic, the emission from the counter-jet should eventually become visible. If the peak of the light curve happens to have been reached in the relativistic phase, then the emission from the counter jet is expected to appear as a secondary peak in the light curve, at about $5 \times t_{NR}$ where t_{NR} is the time in observer's frame of reference when the outflow becomes non-relativistic. Detection of such a signature of the counter jet would be one of the important tests of the hypothesis that the GRBs are due to collimated outflows.

Long duration and well-sampled observations of an afterglow as in the case of GRB 030329, provides an ideal opportunity to look for the signature of counter-jet emission. However, we have shown in this thesis that at low radio frequencies, where the peak of the light curve is reached deep in non-relativistic phase, the signature of the counter-jet is expected to be less clearly discernible - it merely results in a flattening of the peak of the light curve. The shape of the flattening depends on the illumination pattern of the two jets, but the effect is mild and is unfortunately not detectable given the quality of the data available at present. The re-brightening of the light curve expected at higher frequency bands, where the primary peak is reached in the relativistic regime, could also not be probed in the case of GRB030329, as the high frequency follow-up ended well before $5t_{NR}$. Despite our efforts, therefore, we have so far detected no clear signature of the counter-jet emission, and this test of GRB outflow collimation remains inconclusive.

The most commonly discussed signature of GRB afterglow collimation is the "jet break" in the light curve. This arises when an initially tightly collimated outflow starts undergoing significant sideways expansion, as the bulk Lorentz factor of radial motion falls below the inverse of the initial jet opening angle. Being of dynamical origin, this break is expected to be "achromatic", i.e., appear at all wavebands simultaneously. Such breaks have indeed been observed in a few afterglow light curves.

The afterglow of GRB 050401 presented a novel case where the steep decay in brightness in the x-ray band was not accompanied by similar breaks in optical bands. In this thesis we have put forward a suggestion that the optical and the x-ray emission observed from the afterglow of GRB 050401 originated in two physically independent outflows. Our model requires the outflow component primarily responsible for the x-ray emission be collimated more narrowly than that giving rise to the observed optical emission.

Multiple outflow components have been invoked earlier in the literature to explain the broadband behaviour of GRB 030329 afterglow. In this thesis we also cite a couple of more examples, namely GRB 051109A and GRB 050820A which show discrepant optical and X-ray behaviour, the reason for which may lie in multi component afterglows.

One of the long standing questions in astrophysics is what the progenitors of GRBs are. Collapse of a massive star is one of the most favored progenitors of long GRBs. A strong evidence for this comes from the association between GRBs and supernovae. There ought, however, to be another supplementary evidence. Massive stars are known to drive powerful winds during their life time, modifying the circumstellar environment. The wind-modified density profile in the immediate vicinity of the star has a r^{-2} radial dependence, and one expects that the early evolution of the afterglow should bear some signature of this. However it is somewhat puzzling that no conclusive evidence for the wind-modified density profile has so far been found from GRB afterglow light curves. In this thesis we present the case of GRB 050319, which displays a possible signature of a wind-modified circum-burst density profile. We show that the break seen in the multiband optical light curves of the afterglow could be explained as being due to the transition of the circum-burst medium from the wind to constant density medium. We derive a wind bubble radius of $\sim 0.5 - 0.1$ pc.

Appendix-I

List of Publications

List of Publications : Refereed

- ***Multiband Optical Photometry and Bolometric LightCurve of the Type Ia Supernova 2004S*** MNRAS, 360, 662, 2005

  Misra Kuntal, **Kamble, Atish P.**, Bhattacharya D., Ram Sagar

- ***Observations of the Optical Afterglow of GRB 050319 : The Wind-to-ISM Transition in View ?*** ApJ Letters, 664, L5, 2007

  Atish Kamble, L. Resmi, Kuntal Misra (submitted to ApJ Letters)

- ***Optical Afterglow Observations of GRB 050401 : A Case for a Double Jet model*** submitted to MNRAS

  Atish Kamble, Kuntal Misra, D. Bhattacharya, Ram Sagar

- ***GRB 030329 : Detailed study of the GRB 030329 radio afterglow deep into the non-relativistic phase*** Accepted in A&A; [astro-ph/0706.1321]

  van der Horst, A. J., **Atish Kamble**,; Resmi L., Wijers R. A. M. J., Bhattacharya D. et al.

- ***Extensive multiband study of the X-ray rich GRB 050408. A likely off-axis event with an intense energy injection*** A & A Letters, 462, L57, 2007; [astro-ph/0612545]

  A. de Ugarte Postigo et. al. (2006) (Co-authored)

- ***The Dark Nature of GRB 051022 and its host galaxy*** Submitted to A & A A. J. Castro-Tirado et. al. (2006) (Co-authored)

List of Publications : Conference Proceedings

- ***Multiband optical photometry and bolometric light curve of type Ia supernova SN 2004S.*** Bull. Astron. Soc. India, 33, 381, 2005
  Misra Kuntal, **Kamble, Atish P.**, Bhattacharya D., Ram Sagar
  23^{rd} Meeting of the Astronomical Society of India (21^{st} to 23^{rd} Feb. 2005)

- ***GRB 030329 Three Years of Radio Afterglow Monitoring*** To appear in Nuovo Cimento B, proceedings of the Congress "Swift and GRBs: Unveiling the Relativistic Universe", Venice, June 2006; [astroph/0706.1324]
  A. J. van der Horst, **Kamble, Atish P.**, R.A.M.J. Wijers et. al.
  Poster Presentation at the Venice Conference June 2006

- ***GRB 030329 Three Years of Radio Afterglow Monitoring*** Phil. Trans. Roy. Soc. A, vol.365, p.1241, proceedings of the Royal Society Scientific Discussion Meeting, London, September 2006; [astroph/0706.1323]
  A. J. van der Horst, **Kamble, Atish P.**, R.A.M.J. Wijers et. al.
  Key Resutls Paper at the Royal Society Meeting, London Sep. 2006

- ***GRB 050319 : Wind to ISM Transition in View ? and GRB 050401 : Another case for Double Jet***
  Atish Kamble, L. Resmi, Kuntal Misra et. al.
  Poster Presentation at the the Royal Society Meeting, London Sep. 2006

- ***GRB 050319 : Wind to ISM Transition in View ?*** To appear in the Bull. Astron. Soc. India
  24^{th} Meeting of the Astronomical Society of India $6 - 9^{th}$ Feb. 2007
  Kamble, Atish, L. Resmi and Kuntal Misra

- ***GRB 030329 : Three Years of Radio Afterglow Monitoring*** To appear in the Bull. Astron. Soc. India

  24^{th} Meeting of the Astronomical Society of India $6-9^{th}$ Feb. 2007

  Kamble, Atish, L. Resmi, D. Bhattacharya and C. H. Ishwara Chandra

- ***Late Time Evolution of Radio Afterglows***

  $XIII^{th}$ Texas Symposium on Relativistc Astrophysics, Melbourne Dec.2006 D. Bhattacharya, L. Resmi, **Atish Kamble**

List of Publications : GCN-Circulars

- ***GRB070612A: Radio upper limit from GMRT (GCN 6714)***

  Sabyasachi Pal, C.H. IshwaraChandra, Dipankar Bhattacharya and **Atish P. Kamble**

- ***GRB 060218 : GMRT observation (GCN 4832, 4840)***

  Kamble, Atish P.; IshwaraChandra, C. H.; Bhattacharya, D.

- ***GRB 051109B : Nainital upper limits (GCN 4277)***

  Kamble, Atish P.; Misra, K.

- ***GRB 051109A optical observations. (GCN 4259)***

  Misra, K.; **Kamble, Atish P.**; Sahu, D. K.; Srividya, S.; Bama, P.; Anupama, G. C.; Vanniarajan,M. S.

- ***GRB 051105a, observation from Nainital and OSN. (GCN 4204)***

  de Ugarte Postigo, A.; Pandey, S.; Jelinek, M.; CastroTirado,A. J.; Casanova, V.; Gorosabel, J.; Guziy, S.; Mishra, K.; **Kamble, Atish P.**

- ***GRB 051021, optical observations (GCN 4166)***

  Misra, K. ; **Kamble Atish P.**,

- ***XRF 050509c : Radio Upper Limits from GMRT (GCN 3861)***

  Kamble Atish P., IshwarChandra C. H., Bhattacharya D.

- ***GRB050416A : 1 GHz limit from GMRT (GCN 3369)***

  IshwarChandra, C. H., **Kamble Atish P.**, Resmi L.

- ***GRB 050410 : R band Optical Observations (GCN 3226)***

  Misra K ; de Ugarte Postigo, A ; Jelinek, M.; **Kamble, Atish. P.**; Pandey S. B. ; CastroTirado, A. J.

- *GRB 050408 : Optical Observations (GCN 3202)*

  Misra, K. ; Pandey, S. B. ; **Kamble Atish P.**,

- *GRB 050401 : Optical Observations (GCN 3175)*

  Misra, K. ; **Kamble Atish P.**, Pandey, S. B. ;

- *GRB 050319 : R band Observations (GCN 3130)*

  Misra, K. ; **Kamble Atish P.**, Pandey, S. B. ;

Appendix-II

The following publication on supernova 2004S, which is not of direct relevance to the theme of this thesis, is included here for completeness of record. Details of this work will be presented in the PhD thesis of Ms. Kuntal Misra (ARIES, Nainital, India). The contribution of the present author was in the modelling of the light and the color curves of the supernova.