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博士学位论文摘要选登

Swift 时代伽玛射线暴及其余辉的多波段研究

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伽玛射线暴 (简称伽玛暴) 是一种来自太空任意方向的伽玛射线 ($\varepsilon_\gamma \approx 0.1\sim1$ MeV) 脉冲式辐射现象，暴后一般伴随有长时间的低频余辉辐射. 为了对早期余辉乃至瞬时辐射进行多波段观测，美国国家航空航天局 (NASA) 于 2004 年 11 月发射了专门用于伽玛暴研究的 Swift 卫星. 该卫星工作以来，以其快速响应与精确定位的能力和多波段观测的手段取得了一系列令人瞩目的成就 (本文第 1 章将对此进行较为详细的综述), 开创了伽玛暴研究的 Swift 新时代. 基于 Swift 时代以来的研究进展，本文第 2∼6 章将对伽玛暴早期余辉辐射特征以及若干多波段瞬时辐射进行理论解释和模型预言. 此外，作为作者攻读博士学位期间的另一项工作，本文第 7 章将就中子星的演化问题进行一些研究，这将对更好地认识伽玛暴中心能源有所帮助.

Swift 卫星观测到的 X 射线余辉早期缓慢衰减和 X 射线耀发现象，在余辉标准模型下均无法解释，因此本文第 2∼3 章的研究将致力于解决这两个问题. (1) 对于余辉的缓慢衰减，基于已有的脉冲星星风演化理论，我们提出伽玛暴中心磁星吹出的由正负电子对主导的极端相对论性星风作用在伽玛暴冲击波上，将形成相对论性星风泡 (包括一对相对论性正反激波). 数值计算结果和对观测数据的拟合表明，正反激波辐射的叠加可以很好地解释不同程度的余辉光变曲线的变平，并且可将这些变平了的光变曲线大致分为正向和反向激波主导两种类型. (2) 对于 X 射线耀发现象，一般认为起源于中心天体 (比如磁星) 在暴后的间歇性能量释放，而滞后 (相对于瞬时辐射时期而言) 的内激波过程则是将这些能量转化为 X 射线辐射的一种有效途径. 第 3 章对滞后内激波的动力学进行了细致描述，并由此得到了 X 射线耀发的理论光度和光变曲线. 通过与 X 射线耀发观测统计性质的比较，从而可对滞后内激波模型的动力学参数给出限制，而这些参数则直接描述了中心能源所抛出壳层的性质.

能够较好解释 X 射线余辉缓慢衰减现象的能量注入模型主要有两类，分别是相对论星风泡模型和伽玛暴外流体 Lorentz 因子径向分布模型. 为了给这些模型提供更多的观测限制，第 4 章研究了这两类模型所预言的高能余辉辐射特征，主要考虑了电子与低能同步光子的逆 Compton 散射过程. 这两类模型的共同点是能量注入流均以物质主导 (不同的是一为轻子一为重子), 因此可首先为它们建立统一的动力学方程. 其后的数值计算结果表明，两类模型都将预言一个与缓慢衰减的 X 射线余辉相伴随的高能辐射光变平台；但由于相对论星风泡模型中反向激波的相对论性和反向激波化物质的轻子性，它所给出的高能辐射流量将可能比另一个模型高出近 1 个量级，这一区别为 Fermi 卫星的观测鉴别提供了突破口. 此外，我们也对 X 射线耀发的高能辐射进行了类似的计算，发现只有对于相对较亮的 X 射线耀发，其同步自 Compton 高能对应体才可能被 Fermi 卫星观测到.

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除了电磁辐射窗口，第 5 章中还探讨了可能的早期中微子余辉，具体针对类似于 GRB 060218 这样一类低光度伽玛暴 (人们普遍关心在这些暴中是否存在相对论性的冲击波). 观测表明，GRB 060218 的早期 X 射线辐射由超新星激波的热辐射主导，它将对可能存在的相对论性冲击波的辐射性质产生重要影响. 我们详细计算了在热 X 射线光子及其逆 Compton 化成分的作用下，冲击波中高能质子通过 $p\gamma$ 反应和 $\pi^{\pm}$ 介子衰变辐射高能中微子的能力. 鉴于普遍认为的低光度伽玛暴非常高的发生率，这些可能被探测到的余辉中微子将能够为限制低光度伽玛暴瞬时辐射机制提供线索.

第 6 章的研究将从余辉辐射转移到瞬时辐射，具体针对 GRB 080319B 的光学和伽玛射线多波段瞬时辐射. GRB 080319B 最突出的特点是具有一个裸眼可见的光学对应体，其流量比伽玛射线能谱外推到光学波段所得到的流量高出 4 个多量级. 对此我们提出了内激波双成分同步辐射模型，认为内激波中成对出现的正反激波可能具有十分不同的 Lorentz 因子，正是其中相对论性的反向激波产生了伽玛射线辐射，而光学辐射则来自于非相对论性的正向激波. 拟合结果显示：只要伽玛暴外流体的 Lorentz 因子涨落足够大，该模型便能够解释 GRB 080319B 瞬时辐射的基本特征，同时所给出的逆 Compton 辐射 GeV 流量小于或约等于同步 MeV 流量，不会导致高能辐射流量过高的问题.

中子星的 r 模不稳定性将通过引力波辐射和粘滞耗散加热对星体的旋转演化和热演化产生影响. 第 7 章的研究表明这种影响对星体较差旋转的程度有一定的依赖. 较差旋转将使孤立中子星在某一阶段出现轻微的自加速，同时也使粘滞耗散加热显著增强；对于低质量 X 射线双星中的中子星， r 模处于饱和状态的时间在整个吸积循环演化周期中所占的比例也将因为较差旋转而被明显提高. 更为有趣的是，较差旋转还将引起中子星在 60∼90 Hz 频段附近强烈的近似单色的引力波辐射.

最后，第 8 章是作者在完成了以上研究工作之后对伽玛暴及其余辉研究现状的一点思考和展望. 另外，为了方便读者理解和查阅，在附录 A 中摘录和推导了一些与伽玛暴研究相关的物理基础知识，在附录 B 和 C 中则较为系统地介绍了伽玛暴及其余辉的标准模型和一些后标准效应.

Gamma-Ray Bursts and Afterglows: a Multi-Wavelength Study in the Swift Era

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Gamma-ray bursts (GRBs), which are generally followed by long-lasting low-frequency afterglow emission, are short and intense pulses of gamma-rays observed from the sky in arbitrary directions. In order to observe the multi-wavelength emission at the early afterglow phase and even the prompt emission phase, NASA launched the Swift satellite on Nov. 20th 2004. Swift can localize GRBs within about 10 seconds. A brief review on the recent progress in observations and theories in the Swift era is given in Chapter 1. This paper focuses on the features of the early afterglows and the multi-wavelength prompt emission.

In Chapters 2 and 3, we try to explain the shallow-decaying X-ray afterglows and X-ray flares, both of which are unaccountable in the standard afterglow model. (1) It is widely accepted that the shallow decay phase indicates a continuous energy injection into the GRB blast wave, and this energy could be released from the central engine after the burst. Based on the knowledge of the evolution of a pulsar wind, we argue that the injected flow interacting with the GRB blast wave is an ultra-relativistic kinetic-energy flow

(i.e., wind) rather than pure electromagnetic waves. Therefore, a relativistic wind bubble (RWB) including a pair of shocks will be formed. Our numerical calculations and the fitting results show that the emission from an RWB can well account for the X-ray shallow decay phase. (2) For the X-ray flares that are attributed to some intermediate late activities of the central engine, we analyze the detailed dynamics of late internal shocks which directly produce the flare emission. Comparing the theoretical results with the lower limits of the observational luminosities and the profiles of the flare light curves, we find some constraints on the properties of the pre-collision shells, which are directly determined by the central object.

In Chapter 4, we investigate the high-energy afterglow emission during the shallow decay phase in two models, i.e., RWB model and the model with a wide radially spread of Lorentz factors in GRB ejecta (RSE model). We provide a unified description of the dynamics of these two models and calculate the high-energy emission by considering the inverse-Compton (IC) scattering between the electrons and low-energy synchrotron photons. Our results show that, in both models, there is a plateau (even a hump) in high-energy light curves during the shallow decay phase. In particular, the high-energy flux predicted by the RWB model is about one order of magnitude higher than what predicted by the RSE model. These observational signatures would be used to discriminate between these two different energy-injection models. In addition, a similar study on high-energy emission due to the IC mechanism in the late internal shock model shows that the high-energy flares accompanying with the relatively brighter X-ray flares could be detected by Fermi/LAT.

In Chapter 5, neutrino emission from early afterglows of GRB 060218-like GRBs is concerned and neutrinos are expected to be produced from photon-pion interactions in a GRB blast wave which propagates into a dense wind. Relativistic protons are accelerated by an external shock, while target photons are basically provided by the thermal emission from the supernova shock breakout and its IC-scattered component. Because of the estimated high occurrence rate of the low-luminosity GRBs, it will be more possible to detect afterglow neutrinos from a single nearby GRB event of this type by IceCube.

In Chapter 6, we show that the synchrotron emissions respectively produced by the internal forward and reverse shocks could peak at two quite different energy bands if the Lorentz factors of these two types of shocks are significantly different with each other (e.g., the former is Newtonian and the latter is relativistic). Then we investigate whether this scenario is applicable to the case of GRB 080319B and find that a bimodal distribution of the Lorentz factors of shells, peaking at about 400 and 10^5, is required. In addition, this scenario predicts an accompanying IC GeV emission with a luminosity comparable to (not much higher than) that of the synchrotron MeV emission, which can be tested by the Fermi observations in future.

In Chapter 7, considering the effects of reheating due to r-mode dissipation, magnetic braking and accretion, we carefully investigate the long-term spins and thermal evolutions of isolated neutron stars and neutron stars in low-mass X-ray binaries. The role of the r-mode-induced differential rotation on the evolution of neutron stars is taken into account.

Finally, we give some discussions and an outlook in Chapter 8.