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博士学位论文摘要选登

伽玛暴宇宙学的研究

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伽玛射线暴 (简称伽玛暴, gamma-ray burst (GRB)) 是一种来自宇宙空间中的伽玛射线波段流量突然增亮的现象, 最早由 Vela 卫星在 1967 年发现. 1997 年人们通过余辉测得了伽玛暴的红移, 从而确定了其宇宙学的起源. 伽玛暴宇宙学包括用长暴的标准烛光关系限制暗能量和宇宙学参数, 用长暴研究高红移的恒星形成率, 研究金属丰度的演化、尘埃及量子引力等. 伽玛暴的瞬时辐射和余辉阶段多个参量的光度关系的发现, 使我们可以像 Ia 型超新星一样把伽玛暴作为标准烛光来限制宇宙学参数和暗能量, 尤其对于高红移的暗能量, 伽玛暴有很大的优势. 一般认为伽玛暴是由大质量恒星的死亡形成的, 观测发现有一部分伽玛暴与超新星成协, 所以伽玛暴可能是研究高红移的恒星形成率的有效工具. 伽玛暴余辉的光谱是很干净的幂律谱, 金属吸收线可以很容易地从伽玛暴的余辉中提取, 通过分析金属吸收线, 我们能得到早期宇宙的金属丰度的演化及再电离的历史.

本论文的研究内容是伽玛暴宇宙学, 这是一个崭新的高速发展的方向. 本文先对伽玛暴和暗能量的研究做一综述, 然后对本人的几个具体工作进行详细的介绍. 论文的具体组成如下:

第 1 章是伽玛暴及其余辉的研究现状综述. 首先介绍了各个时代伽玛暴的研究进展, 主要介绍了 Swift 卫星和 Fermi 卫星观测的最新结果. 伽玛暴的理论方面介绍了伽玛暴的火球模型和余辉的标准模型.

第 2 章介绍了标准宇宙学模型以及与暗能量相关的天文观测和暗能量模型. 最后我们介绍了伽玛暴宇宙学的研究进展, 包括限制宇宙学参数和暗能量, 计算恒星形成率, 研究金属丰度演化和再电离、尘埃以及限制量子引力等. 本人即将投稿和参与的一些工作也在本章的相关部分介绍.

第 3 章我们用伽玛暴和最新的天文观测来限制宇宙学参数和暗能量. 由于 Ia 型超新星的最高红移为 1.7, 加入高红移的伽玛暴后可以更好地限制暗能量. 我们用的数据包括 Ia 型超新星、宇宙微波背景辐射、重子声速振荡、 X 射线气体质量分数、伽玛暴和扰动增长因子. 研究发现 ΛCDM 是与观测符合得最好的模型, 拐折红移 $z_{\rm T}$ 的大小从 $0.40^{+0.14}_{-0.08}$ 到 $0.65^{+0.10}_{-0.05}$ (1σ). 这是第 1 次把伽玛暴和这些观测数据相结合来研究宇宙学参数、暗能量和拐折红移.

第 4 章我们应用伽玛暴、 Ia 型超新星、宇宙微波背景辐射和重子声速振荡来研究早期暗能量宇宙学. 在宇宙早期存在的很稀薄的暗能量对宇宙结构形成有很大影响, 研究它的性质很重要. 我们提出伽玛暴是研究早期暗能量的有效工具, 因为早期暗能量只在宇宙早期起作用. 通过研究发现, 早期暗能量的能量密度小于 0.03, 线性扰动增长因子大小为 0.66.

第 5 章我们用与模型无关的方法来限制暗能量的状态方程 $w(z)$. 在许多描述暗能量的参数中, 状态方程是最重要的. 状态方程是否随时间演化和怎样随时间演化, 对我们区分暗能量模型有很重要的作用. 以前的研究只用了低红移的数据, 我们的工作加入伽玛暴限制高红移的状态方程. 我们发现红移大于 1.7 的状态方程 $w(z) < 0$, 这是第 1 次用与模型无关的方法得到的对红移大于 1.7 的状态方程的限制. 在 95.4% 置信度区间内, 发现状态方程偏离 -1.

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第 6 章我们研究宇宙结构学参数，并用其来区分暗能量和修正引力模型．暗能量和修正引力的模型都能驱动宇宙加速膨胀，但是本质不一样．如何从观测上区分这两类模型，是现在暗能量研究的重要问题．我们把光度距离展开到红移 z 的 4 阶项，得到 snap 参数．伽玛暴可以限制 snap 参数，我们发现不同模型下的 snap 参数有很大差别，所以可以用 snap 参数来区分模型．

第 7 章我们用长暴来研究高红移处的恒星形成率． Swift 的观测表明在高红移处的伽玛暴比由恒星形成率预言的要多，我们发现用随红移演化的初始质量函数可以很好地解释伽玛暴的爆发率与恒星形成率的不一致．考虑伽玛暴的爆发率与恒星形成率和金属丰度的演化相关，我们测量红移到 8.2 的恒星形成率．计算中我们还考虑了背景宇宙学的影响．

第 8 章我们研究了第 1 代恒星产生的伽玛暴的观测特征和用伽玛暴余辉光谱的金属吸收线来研究金属增丰．第 1 代恒星产生的伽玛暴与低红移伽玛暴最大的不同是伽玛暴的暴周环境，我们发现暴周环境密度大约与 $(1+z)$ 成正比．第 1 代星系中产生的伽玛暴余辉光谱中的金属吸收线可以用于研究高红移的金属增丰．我们发现由第 1 代超新星爆发产生的金属都以低电离态存在 (C II, O I, Si II 及 Fe II)．当伽玛暴的余辉穿过被金属污染的区域，将会在伽玛暴的谱上产生金属吸收线．由于金属增丰是各向异性的，所以在不同的视线方向产生的吸收线将有很大的不同．

最后，第 9 章中是作者在完成了以上研究工作之后对伽玛暴宇宙学前景的一些展望．

Gamma-ray Burst Cosmology

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Gamma-ray bursts (GRBs) are brief flashes of gamma-rays occurring at cosmological distances. GRB was discovered by Vela satellite in 1967. The discovery of afterglows in 1997 made it possible to measure the GRBs' redshifts and confirmed the cosmological origin. GRB cosmology includes utilizing long GRBs as standard candles to constrain the dark energy and cosmological parameters, measuring the high-redshift star formation rate (SFR), probing the metal enrichment history of the universe, dust, quantum gravity, etc. The correlations between GRB observables in the prompt emission and afterglow phases were discovered, so we can use these correlations as standard candles to constrain the cosmological parameters and dark energy, especially at high redshifts. Observations show that long GRBs may be associated with supernovae. So long GRBs are promising tools to measure the high-redshift SFR. GRB afterglows have a smooth continuum, so the extraction of IGM absorption features from the spectrum is very easy. The information of metal enrichment history and reionization can be obtained from the absorption lines.

In this thesis, we investigate the high-redshift cosmology using GRBs, called GRB cosmology. This is a new and fast developing field. The structure of this thesis is as follows.

In the first chapter, we introduce the progress of GRB studies. First we introduce the progress of GRB studies in various satellite eras, mainly in the Swift and Fermi eras. The fireball model and standard afterglow model are also presented.

In chapter 2, we introduce the standard cosmology model, astronomical observations and dark energy models. Then progress on the GRB cosmology studies is introduced. Some of my works including what to be submitted are also introduced in this chapter.

In chapter 3, we present our studies on constraining the cosmological parameters and dark energy using latest observations. We use SNe Ia, GRBs, CMB, BAO, the X-ray gas mass fraction in clusters and the linear growth rate of perturbations, and find that the ΛCDM is the best fitted model. The transition redshift $z_{\rm T}$ is from $0.40^{+0.14}_{-0.08}$ to $0.65^{+0.10}_{-0.05}$. This is the first time to combine GRBs with other observations to constrain the cosmological parameters, dark energy and transition redshift.

In chapter 4, we investigate the early dark energy model using GRBs, SNe Ia, CMB and BAO. The negligible dark energy at high redshift will influence the growth of cosmic structures and leave observable signatures that are different from the standard cosmology. We propose that GRBs are promising tools to study the early dark energy. We find that the fractional dark energy density is less than 0.03 and the linear growth index of perturbations is 0.66.

In chapter 5, we use a model-independent method to constrain the dark energy equation of state (EOS) $w(z)$. Among the parameters describing the properties of dark energy, EOS is the most important. Whether and how it evolves with time are crucial in distinguishing different cosmological models. In our analysis, we include high-redshift GRBs. We find that $w(z) < 0$ at $z > 1.7$, and EOS deviates from the cosmological constant at $z > 0.5$ at 95.4% confidence level.

In chapter 6, we probe the cosmographic parameters to distinguish between the dark energy and modified gravity models. These two families of models can drive the universe to acclerate. We first derive the expressions of deceleration, jerk and snap parameters in the dark energy and modified gravity models. The snap parameters in these models are different, so they can be used to distinguish between the models.

In chapter 7, we measure the high-redshift SFR using long GRBs. Swift observations reveal that the number of high-redshift GRBs is larger than the predication from SFR. We find that the evolving initial mass function can interpret this discrepancy. We study the high-redshift SFR up to $z \sim 8.2$ considering the Swift GRBs tracing the star formation history and the cosmic metallicity evolution in different background cosmological models.

In chapter 8, we present the observational signatures of Pop III GRBs and study the pregalactic metal enrichment with the metal absorption lines in the GRB spectrum from first galaxy. We focus on the unusual circumburst environment inside the systems that hosted Pop III stars. The metals in the first galaxies produced by the first supernova explosion are likely to reside in the low-ionization states (C II, O I, Si II and Fe II). When GRB afterglow goes through the metal polluted region, the metal absorption lines may appear. The topology of metal enrichment could be highly inhomogeneous, so along different lines of sight, the metal absorption lines may show distinct signatures.

A summary of the open questions in GRB cosmology filed is presented in chapter 9.