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Tracing Cosmic Chemical Evolution with GRBs

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Abundance measurements with bright background light sources, such as quasars and GRBs, probe the large-scale distribution and physical state of evolving, coupled gas- star - dark matter structures in the Universe. Not all baryons inferred from BBN and the CMB are accounted for in the local Universe; a significant fraction resides in warm-hot tenuous gas filaments tracing the large-scale distribution of dark matter. Understanding the chemo-dynamics of these structures can be advanced with sensitive X-ray studies of emission from diffuse baryons in the warm-hot medium residing in clusters and the filamentary cosmic web, and in absorption with bright, distant sources, in particular GRBs. Supernovae and galaxies are bright enough to be traced to high redshifts, but the diffuse gas in their vicinity is not luminous enough to be detectable in emission at such distances. This diffuse component can be probed with absorption spectroscopy of bright background sources. GRBs, associated with massive stars, provide beacons that may trace star formation to the first generations. Their large brightness allows abundances to be measured in early, small proto-galaxies, and to trace them to the era of re-ionization, at $z > 6$.

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[1] Speaker

1. Introduction

Investigations of the formation and evolution of cosmic structures and the chemical abundances of stars and the interstellar- and intergalactic medium are at the frontier of observational astrophysics. Absorption studies of the structured universe with bright background light sources, such as quasars and Gamma Ray Bursts (GRBs), probes the large-scale distribution and physical state of coupled gas- star - dark matter underlying the basic building blocks of the universe. Not all of the baryons in the local universe are currently accounted for, some reside in the hard to detect warm-hot tenuous gas tracing underlying dark matter. Studies of cosmic chemical evolution would benefit significantly from sensitive, high-resolution, wide FoV imaging X-ray spectroscopy of baryons in the Warm-Hot-Ionized Medium (WHIM) located in and between galaxy clusters, and in the amazing structures of the cosmic web of filaments found in LSS simulations. The mysterious dark components of the universe and the luminous, baryonic components are coupled by gravity and feedback processes (star formation and subsequent seller winds and supernovae). Probing the links between these components is required to better understand how the universe transitioned from the dark ages to the present. Directly tracing cosmic chemical evolution back to the very first stars is a daunting task. Much attention is given to near-field cosmology, where extremely low abundance halo stars reveal the very early phase of the Galaxy's evolution. But the limiting factor is the confinement to our own Galaxy. GRBs offer a way to overcome this limitation via rapid spectroscopy of their afterglows, revealing abundances in distant proto-galaxies as small as the Magellanic clouds. Long-soft GRBs are believed to be produced during the final stages of the evolution of rotating, metal poor massive stars, while short-hard GRBs may be associated with merging compact binary systems (e.g., a neutron star binary). Both classes trace star fomation with little delay, and thus offer a unique probe of the high redshift Universe. Their luminosities allow easy detection, even at large distances, and their afterglows provide a valuable (albeit rapidly decaying) source of light for spectroscopic studies of the intervening intergalactic gas.

2. Gamma-Ray Bursts as Beacons

The cosmic GRBs rate is about one per day, to be contrasted with a global rate of a few core-collapse Supernovae (ccSNe) per second. They are easily detected above the Earth's atmosphere, and if localized accurately and rapidly their afterglows can be studied from the ground even with small telescopes. Afterglows can serve as powerful tools to probe properties of the gas along the line of sight, but spectroscopy must be carried out quickly. The need for rapid response and sustained monitoring requires a dedicated global effort, in space and on the ground. After their discovery in the 60ies [1] with the Vela satellites, the following decades established their isotropic angular distribution, but they remained undetected outside of the γ-ray regime [2]. The lack of accurate and rapid positions proved to be the bottleneck. Data from the Compton Gamma-Ray Observatory (1991-1999) confirmed earlier indications of a bimodal duration distribution, suggesting multiple classes [3]. X-ray detectors on BeppoSAX (1996-2002) for the first time provided rapid, accurate localization, and discovered the first X-ray afterglow from GRB970228 [4], which led to the discovery of the first optical afterglow [5][6]. Measurements of redshifts and identification of host galaxies followed quickly. Their large fluences and distances imply the release of challenging amounts of energy (~ 10^3 B; where 1 B = 1 Bethe = 10^{51} ergs), a problem alleviated via beamed (θ ~ degrees) jet emission. The release of such large amounts of energy leads to a fire-"ball", opaque to its own radiation, accelerated to Lorentz factors $\Gamma >> 1$. Internal dissipation of energy via shocks of colliding "shells" leads to the prompt GRB phase, but a fraction remains stored in bulk motion. Eventually the ejecta interact with a circum-burst medium via external shocks, generating afterglow emission that can be detected for a long time. The dynamics of these flows, and assuming synchrotron (jitter-) radiation as the dominant radiation process, implies a flux density; $f_\nu \propto t^{-\alpha}$, where typically $\alpha \sim 1$ and time (t) is measured in days [7,8,9,10]. This emission covers a broad spectral range and thus provides a powerful background source for absorption studies. A jet-break in the lightcurve, yields information on the jet opening angle, θ, and thus corrects the energy estimated from the fluence and the luminosity distance, $D_L(z)$. Jet angles of order degrees results in an energy scale of ~ 1 B, with a relatively narrow distribution [11]. This scenario of relativistic, jetted outflows has been confirmed with the observation of achromatic jet breaks in the optical regime, but a lack of X-ray breaks, or their late appearance [12], led some to favor alternative models [13].

GRB afterglow spectroscopy frequently reveals large neutral hydrogen column densities ($N_{HI} > 10^{20}$ cm^{-2}, called DLAs, Damped Lyman Alpha systems). Metal absorption lines imply abundances that are typically less than solar and exhibit a mild trend of cosmic evolution [14]. However, the sample is still small and the quality of the spectra often insufficient for accurate abundance determinations. To utilize GRBs as probes of cosmic chemical evolution (CCE) we must improve resources (network of telescopes and spectrographs). Higher rates from new GRB detectors, e.g., EXIST [15], require enhanced facilities and human resources. More than 80% of Swift-detected GRBs were localized with the X-ray telescope (XRT), and for ~40% of these events afterglow observations led to a measured redshift. There is no consensus on the reasons for the non-detection of so many GRBs. Explanations include absorption in the interstellar medium of the host galaxy, and a significant fraction of high-z GRBs [16,17]. "Dark" GRBs may represent a very distant population. Swift GRBs have $\langle z \rangle \sim 2.7$ [18] and the z-distribution is roughly consistent with models where the GRB rate traces the cosmic star formation rate [19].

3. Tracing Cosmic Chemical Evolution with GRBs

Supernovae and galaxies are detected to z ~ 2 and z ~ 7, respectively, but diffuse gas in their vicinity is not luminous enough to be detectable in emission at these distances. However, it can be probed in absorption. GRBs are unique beacons for this task. GRBs track star formation with little delay, and possibly reach the Pop III epoch. Their afterglows provide opportunities to measure abundances in small proto-galaxies, and trace their changes beyond z ~ 6. Afterglows probe the host and the intervening IGM. Kann et al. [20] showed that typically only a modest amount of extinction (< 0.4 mag) is present in hosts (but see [32]). This is surprising, as the association with massive stars [21] suggests that they should be affected by extinction by dust in the star-forming regions in metal poor, sub-luminous, irregular host galaxies [22]. One of the highest redshift bursts is GRB 050904 at z = 6.3 [23], originally identified as a high-z candidate based on multi-color observations [24]. GRB060927 (z = 5.5) is another example of a GRB near the end of the re-ionization epoch [25]. Finding high-z GRBs is the goal of dedicated projects, e.g., GROND [26], and future space missions, like EXIST [15], CASTER [27], or *Xenia* [28], which could performe X-ray spectroscopy within minutes. Bursts from the earliest stars would provide a spectacular glimpse into pre-galactic epochs. Absorption lines establish abundances often not available from ground based spectroscopy [33]. The study of CCE and the GRB-SN connection (here iron is a key parameter) would be placed on firmer ground. Star formation in the early universe [17] has an Initial Mass Function biased to larger masses, affecting mass-loss of stars and their subsequent explosive fates [29]. Most massive stars today explode as Type II core collapse supernovae (ccSNe or SNII), but a massive Pop III star more likely dies by pair instability [29]. The universe was fully re-ionised by z ~ 6 [e.g., 25], but we do not know the details of this extended, inhomogeneous transition [34]. Many sightlines are needed to explore this epoch. GRBs provide a powerful tool [30] for this task, but their transient nature requires unique observational capabilities, such as combined wide-FoV monitoring and fast re-pointing of high-resolution X-ray spectrometers. Probing the cosmic baryon history is a new frontier [31][34], and GRBs are going to play an increasingly important role in this endeavor.

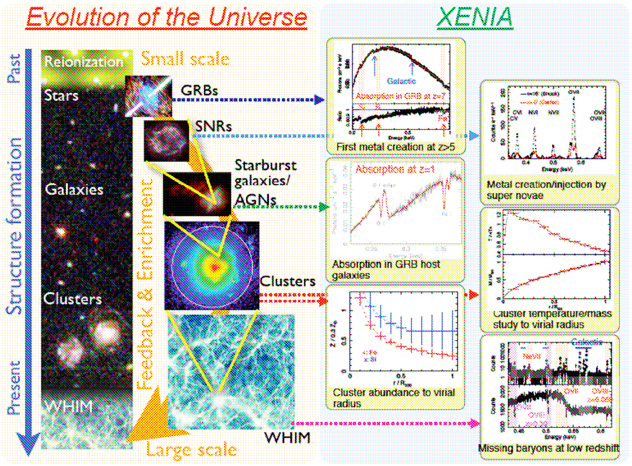

FIG. 1. ***Xenia***: Many nuclei never make it into stars, but remain in a diffuse baryonic component tracing the evolving dark matter. Winds from massive stars and their supernovae affect galaxy formation on large scales, inflows into dark matter potential wells encounter SN-driven outflows. X-ray absorption yields host abundances, and emission lines from nearby clusters probe baryons beyond their virial radii.

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