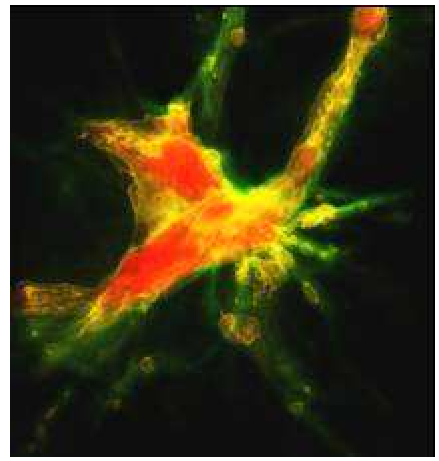
Tracing the Cosmic Star Formation History to its Beginnings: Gamma-Ray Bursts as Tools

Executive Summary

The star formation rate (SFR) is the key driver of structure evolution in the ISM, and strongly influences galaxy formation and evolution via energy, momentum, and chemical feedback from subsequent stellar winds and supernova explosions. UV emission from the first generation of massive stars is most likely responsible for the re-ionization of the Universe at z > 6, and the integrated light of evolving stellar populations generated a diffuse cosmic IR-X-ray background. Starlight, and its associated reprocessed IR-component, creates a formidable optical depth for TeV photons, and low-energy γ-rays escaping from supernovae, mostly of SNIa origin, generate a unique MeV background. IR-UV continuum emission and optical line emission can be used to determine the specific SFR in galaxies, and an extinction corrected rate density, SFR(z), can be estimated. Direct probes, such as GRBs are needed to trace star formation to the highest redshifts.

Gamma Ray Bursts (GRBs) are associated with the final stages of the lives of massive stars. They are excellent tools for measuring the cosmic SFR, back to the first galaxies forming at z ~10 in the simulation below (Greif et al. 2008)



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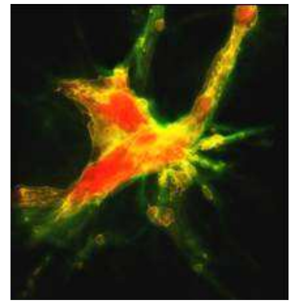
Submitted to Panels: **SSE**: Stars & Stellar Evolution, **CFP**: Cosmology and Fundamental Physics, and **GCT:** The Galaxies across Cosmic Time.

Associated Missions: EXIST

Synergy: JWST, Fermi, H.E.S.S. , VERITAS, MAGIC: High Performance Computing (Blue Waters machine)

KEY QUESTIONS

When did the first stars form? – z(1st)
What is the cosmic star formation rate history? – SFR(z)
How does the SFR(z) build up the cosmic photon field? $F_\nu(\nu)$
How does the SFR(z) build up the diffuse neutrino background?
What is the optical depth of the Universe in the GeV-Tev regime?



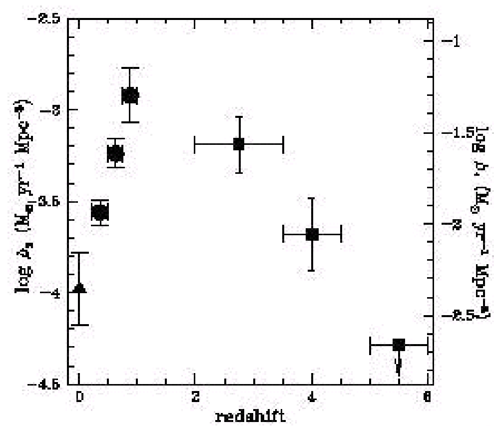
The study of *star and galaxy formation* in the early Universe is in its beginning stages. Simulations suggest a strong bias of the Initial Mass Function (IMF) to larger stellar masses with decreasing metallicity and thus, on average, higher redshift (e.g., Abel et al. 2000; Bromm & Loeb 2007). In turn this affects the mass-loss of these early stars, and their subsequent explosions. Low metallicity implies low mass loss, so that early stars will be more massive than present stars, even if the IMF were universal. While most massive stars today explode as Type II core collapse supernovae (ccSNe or SNII), a near zero-metallicity star (Pop III) of ~ 150 M_o more likely dies by pair instability (e.g., Heger et al. 2003). Isotopic yields of supernovae from this population exhibit marked patterns in the odd-Z element range 7 to 13 (Heger & Woosley 2008). To date, the nucleosynthesis signature of pair-SNe has not been found in metal poor stars. Feedback on the environment from the first generation of supernovae is different than in a present-day galaxy, and star formation today takes place in dense molecular clouds, while in the early Universe it was hampered by inefficient cooling in pristine H-He environments. However, the first generation of supernovae quickly enriched the gas, so that subsequent stellar generations could be born from more efficiently cooling metal-enriched gas. The cosmic dark ages persisted until the first gas clouds collapsed into gravitationally-bound systems. The first light from very massive, initially metal free stars re-ionized the Universe by z ~ 6 (e.g., Fan, et al. 2007; Loeb, Ferrara, and Ellis 2008), and shortly thereafter the demise of the first stellar population launched the era of Population II stars. To better understand the process of star formation in metal-poor environments, we seek to determine when star formation started, and how the rate density changed over time.

Early star formation may have started with Population III stars at z > 20 (Bromm e al. 1999; Abel, et al. 1999), and it may have undergone several episodes (e.g., Fan et al. 2007). Establishing the origin of the ionizing radiation is an outstanding challenge in observational cosmology. Probably the most direct method to do so is the use of long-soft GRBs, for which the delay between the formation of the massive progenitor and its collapse (the burst) is short. The association of long duration Gamma Ray Bursts with the final stages of the evolution of massive stars has been established with photometry, via late "bumps" in their optical afterglows and in some cases with spectroscopic signatures (Woosley & Bloom 2006), and their correlation with light in nearby galaxies (Fruchter, et al. 2006). Their afterglow emission offers a tool for absorption line spectroscopy of their host galaxy environments and any material along their lines of sight. With typical redshifts of z ~ 2, and a present record of z = 6.7 for GRB 080913 (Greiner et al. 2008), it is clear that GRBs indeed offer a powerful tool to probe cosmic evolution to the earliest epochs of star formation. They are easy to detect to large distances (Lamb & Reichart 2000), and world-wide rapid response networks, including several sensitive optical spectrometers on large aperture telescopes, are ready to establish redshifts for most bursts at medium- to high redshifts (z < 7). Beyond these distances IR observations in conjunction with wide-FoV γ-ray monitoring would extend the range into the era of reionization. At very high redshifts even the deepest ground-based studies are unable to pinpoint a small star forming proto-galaxy, similar to the LMC or SMC, but GRBs are bright signposts of such systems and simultaneously offer bright, albeit rapidly fading probes of such early structures.

Present Status and Implications of SFR(z)

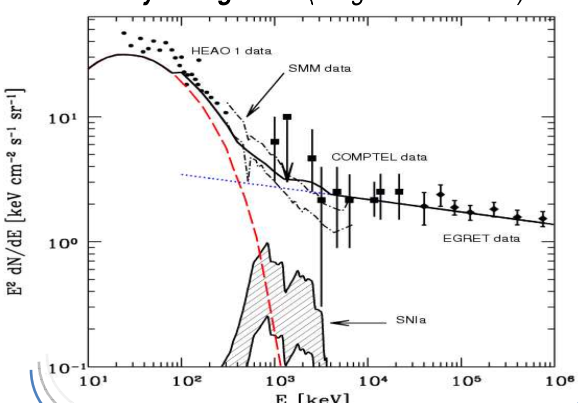
The Milky Way exhibits an integrated star formation rate of a few solar masses per year (see Diehl et al. 2006 for a summary of various tracers and estimates). Radioactive isotopes like ^{26}Al and ^{60}Fe, ejected during the explosions of massive stars and prior by the strong winds of their progenitors, trace the global, galactic star formation activity well. The local galaxy density of ~ 10^{-2} Mpc^{-3} thus implies a local SFR-density of a few solar masses per year per cubic Mpc. On a larger scale, γ-rays from supernovae produce a cumulative background in the MeV regime (Fig. 1), which can be used to determine the global star formation history of the universe (Watanabe et al. 2003). Using observations of the Hubble Deep Field (HDF) Madau (1997) and collaborators determined the SFR-density to z ~ 5 (Fig 2), which demonstrated that this key function had a maximum at z ~ 1-2, and a relatively fast decline beyond. Shortly after this study, a flurry of activities led to improved estimates, with better low-z calibrations and taking dust extinction into account. The SFR(z) function moved up substantially, and it's high-z tail flattened out.

Fig. 2: The classic Madau plot: Star formation rate density (per co-moving volume) vs. z from the Hubble Deep Field (Madau 1997).



The measurement of SFR(z) is essential for the determination of the MeV background mentioned above, and the associated neutrino background in the ~10 MeV-window, which may soon be detectable by Super-Kamiokande (Horiuchi, Beacom & Dwek 2009). These neutrinos probe the dense, hot interiors of proto-neutron stars at the heart of core-collapse SNe. In addition to direct SFR measures from rates of SNIa and SNII in the "nearby" Universe (the limit of direct SN searches is approaching z~2, e.g., Riess et al. 2001), these two backgrounds offer a valuable, cumulative measurement of the SFR function. It must be mentioned that all these methods require a conversion from event rates to star formation rates, which inevitably involves the Initial Mass Function (IMF), and various assumptions about its evolution and dependence on environment.

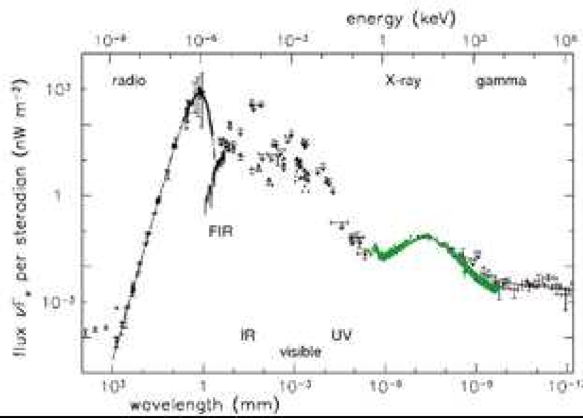
Fig 1. MeV gamma-rays emerging from supernovae (mostly due to ^{56}Ni from SNIa) produce a cumulative diffuse ***γ-ray background*** *(Strigari et al. 2005)*



Extending the Madau plot to redshifts larger than those reachable with supernovae is an important goal for observational cosmology. Directly tracing SFR(z) back to the first stars is an even more daunting task. Here, GRBs offer a unique way to accomplish this goal. The long-soft class of GRBs is believed to be produced during the final stages of the evolution of some massive stars, when an accretion disk forms around a black hole and enormous energy release in its vicinity drives ultra-relativistic jets through the star along its rotation axis. Short-hard GRBs are also believed to be associated with a black hole - accretion disk – jet system, but with merging binary systems of compact stars (e.g., a neutron star binary) as progenitors. Both of these source classes trace, more or less directly, the cosmic star formation history, and thus offer a probe of the high-z behavior of SFR(z). A large sample of GRBs with measured redshifts (either from rapid afterglow spectroscopy on the ground, or with a dedicated space-based approach) will yield a mapping of GRB-rate to SFR(z), with model assumptions about the connection between stellar metallicity and likelihood of GRB progenitor formation. Kistler et al. (2008) have argued in favor of a GRB rate that increases with z more rapidly than SFR(z), while Faucher-Giguere et al. (2008) argue in favor of a 1-1 relationship.

The Extragalactic Background Light (EBL) across a wide wavelengths range from the radio- to the high-energy regime (Fig. 3) is in part truly diffuse and in part composed of emission from unresolved populations of various sources. The truly diffuse Cosmic Microwave Background (CMB) is a relic of the early history of the universe, but all other bands measure integrated contributions from stars and accreting sources during the buildup of galaxies and clusters of galaxies. Knowledge of SFR(z) is critical in the re-construction of this meta-galactic radiation field as a function of time (Kneiske et al. 2002; Primack et al. 2008). We can utilize the diffuse extragalactic background spectrum, and its evolution in time, as a probe of cosmic structure formation and evolution. Generations of stars produced a growing UV-Optical-IR component of the EBL, and reprocessing by dust in the interstellar medium (ISM) added further IR components. This background destroys photons of very high energies via pair creation, which allows us to probe the EBL with appropriate sources. However, while TeV emission from nearby blazars at z < 0.1 is strongly suppressed, GeV emission from GRBs is suppressed as well, but only after propagation through much greater distances (Grindlay et al. 2007; Hartmann 2007; Stecker 2007). The opacity of the Universe directly relates to the cosmic star formation history, and the accurate determination of SFR(z) is an essential requirement for all models of photon-photon pair creation extinction corrections to be applied to GeV-TeV sources. NASA's Fermi mission is now creating a rapidly growing data base of GeV-spectra of nearby AGNs and distant GRBs. AGILE is contributing as well, and ground-based TeV observatories, H.E.S.S., MAGIC, and VERITAS, are complementing this with TeV data. The utilization of these data requires proper corrections for high-energy extinction via pair creation off the EBL, and thus implies the need for measuring SFR(z). It is important to note that the nearby Universe quickly becomes opaque at TeV energies, but the range of GeV photons is much larger, so that it is crucial to establish the photon SED in the Universe as a function of time, and not just the present-day spectrum (Fig. 3). This task is deeply connected to the task of measuring SFR(z). The synergy between space-based GeV observations and ground-based TeV observations is leading to startling results on the EBL, raising questions on the transparency or opaqueness of the Universe (Aharonian et al. 2008; Stecker & Scully 2009).

Fig 3: The EBL (adapted from Fig. 1.18 of Sparke and Gallagher 2007) across a large dynamic range. This background, properly corrected for evolution, is the source of large opacity for GeV-TeV photons from cosmic



Rate expectations: We do know that GRBs occur as early as z = 6.7 (current record holder is GRB 080913, e.g., Greiner et al. 2008). However, the scientific value of establishing the full SFR(z) function in the high-z regime does not lie in setting records, but using the observed rate distribution to test the current paradigm of a tight GRB-SF connection. This not only answers the key questions about the 1st stars, and the build-up of the various backgrounds, it allows further development of GRB theory. It is likely that metallicity effects in progenitor systems, and fundamental issues such as binary formation in low-metal environments will lead to systematic trends in the GRB/SF-ratio. Furthermore, short-hard GRB resulting from the merger of compact binaries (NS-NS, or NS-BH) have significant delays between star formation and final merger event, so that these time delays may become noticeable at very large redshifts (e.g., Belczynski et al. 2009). Estimates for the fraction of GRBs beyond a given redshift are uncertain due to a number of free model parameters, but most authors find that ~10% of all GRBs occur beyond z ~ 5. Thus the detection and classification of GRBs as a function of z for a significant sample requires a mission that goes beyond Swift in sensitivity and ability to determine z autonomously, i.e., without further delay due to constraints from the observatories of the world-wide response network. Measuring SFR(z) to z > 10 is an observational goal that is within reach with present technology. This function is important for many astronomical studies, as described above, it provides an essential constraint on models for the formation of Pop III and extreme Pop II stars, and it advances our basic understanding of GRBs via constraints on progenitors.

Fig. 4: GRBs as tracers of the cosmic star formation history.

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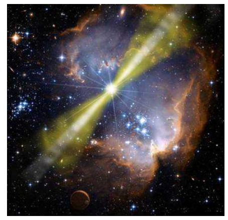

FROM SCIENTIFIC GOALS TO OBSERVATIONAL REQUIREMENTS

To establish SFR(z) beyond z ~ 5, a sensitive large-FOV hard X-ray (soft γ-ray) survey is required to find an appreciable number of high-z bursts. Band et al. (2008) carried out a study of the performance of a simulated instrument based on an earlier version of the EXIST design (Grindlay et al. 2006), and shows that bursts beyond z = 10 can in fact be detected, and localized for follow-up studies. At these high redshifts it is desirable to have IR follow-up spectroscopy directly with the same spacecraft, i.e. minimizing delays that are inevitable for ground-based responses. The new EXIST design as well as the SMEX mission JANUS include IR capabilities. Optical emission from the GRB afterglow is highly suppressed by absorption in the neutral IGM at high-z, but a new concept for direct redshift determinations of GRBs at distances even as large as z ~ 20 is based on measurements of resonant nuclear lines (GRIPS; Greiner et al. 2008). Thus technology is in place to obtain a significant sample of high-z bursts, and thus to measure the GRB-SFR(z) function into the era of reionization.

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