GRBs as Standard Candles: Toward GRB Cosmology

A study presenting the most comprehensive analysis until now of gamma-ray bursts (GRBs) detected by the Neil Gehrels Swift Observatory (Swift) has been presented in a recent article (https://ui.adsabs.harvard.edu/abs/2020arXiv200906740S/abstract), arXiv:2009.06740, to appear in *The Astrophysical Journal Supplements Series*. The analysis was performed by an international team led by Maria Giovanna Dainotti (she has become a Senior Research Scientist of iTHEMS, RIKEN from 1st Oct. 2020, and currently Assistant Professor at Jagiellonian University in Krakow, Poland and an affiliate scientist at the Space Science Institute in Boulder, Colorado).

Their work builds on previous research by Dainotti and her collaborators covered in 2016 and 2017, and is a major step toward enabling astrophysicists to use GRBs, which are some of the most powerful high-energy electromagnetic events known in the Universe, as standard candles.

Standard candles are objects with fixed luminosities that can be calculated by taking advantage of well-established relationships between an object's luminosity and its physical properties—relationships that are independent of the object's distance. Such objects enable the calculation of accurate astronomical distances.

The furthest well-established standard candles to date have been Type Ia supernovae, but GRBs have been observed at much greater distances (up to 13.2 billion light years vs. 11 billion light years for Type Ia supernovae). Thus, GRBs could provide accurate distances to events that happened only a few hundred millions of years after the Big Bang, very close to when stars began to form in the Universe.

The challenge in demonstrating the usefulness of GRBs as standard candles arises because different GRBs vary dramatically not only in their behaviors, but in their physical origins and progenitor environments as well. For example, the duration of observable emission from GRBs can vary from milliseconds to tens of minutes, resulting in short-duration GRBs, long-duration GRBs, and ultra-long-duration GRBs. Also, their initial bursts of gamma rays can give way to a dizzying variety of X-rays, ultraviolet and optical light, all the way down to microwaves. Further, they can originate from special kinds of supernovae, collisions between neutron stars, or between black holes and neutron stars.

However, the discovery that almost 50% of GRBs observed by Swift display a flat "plateau" emission in their X-ray light curves told Dainotti and her collaborators that they just might be able to gather some GRBs into a common group.

The team analyzed 455 Swift GRBs and pinpointed relationships between this plateau emission and several observed properties: the peak luminosity (L_{peak}) during the initial burst, called the prompt emission; the time at the end of the plateau phase (T_a); and the luminosity detected at the end of the plateau phase (L_a). These quantities are all shown in Figure 1, along with the plateau phase and the peak flux, which determines the peak luminosity.

Plotting the three observational properties on a three-dimensional graph revealed a relationship Dainotti has dubbed the "3D Fundamental Plane," due to the fact that most of the points fall neatly onto a plane, indicated by the gray region in Figure 2.

Dainotti and her collaborators have now been able to take the next steps necessary to define GRBs as standard candles—connecting these observations to certain physical properties of a GRB.

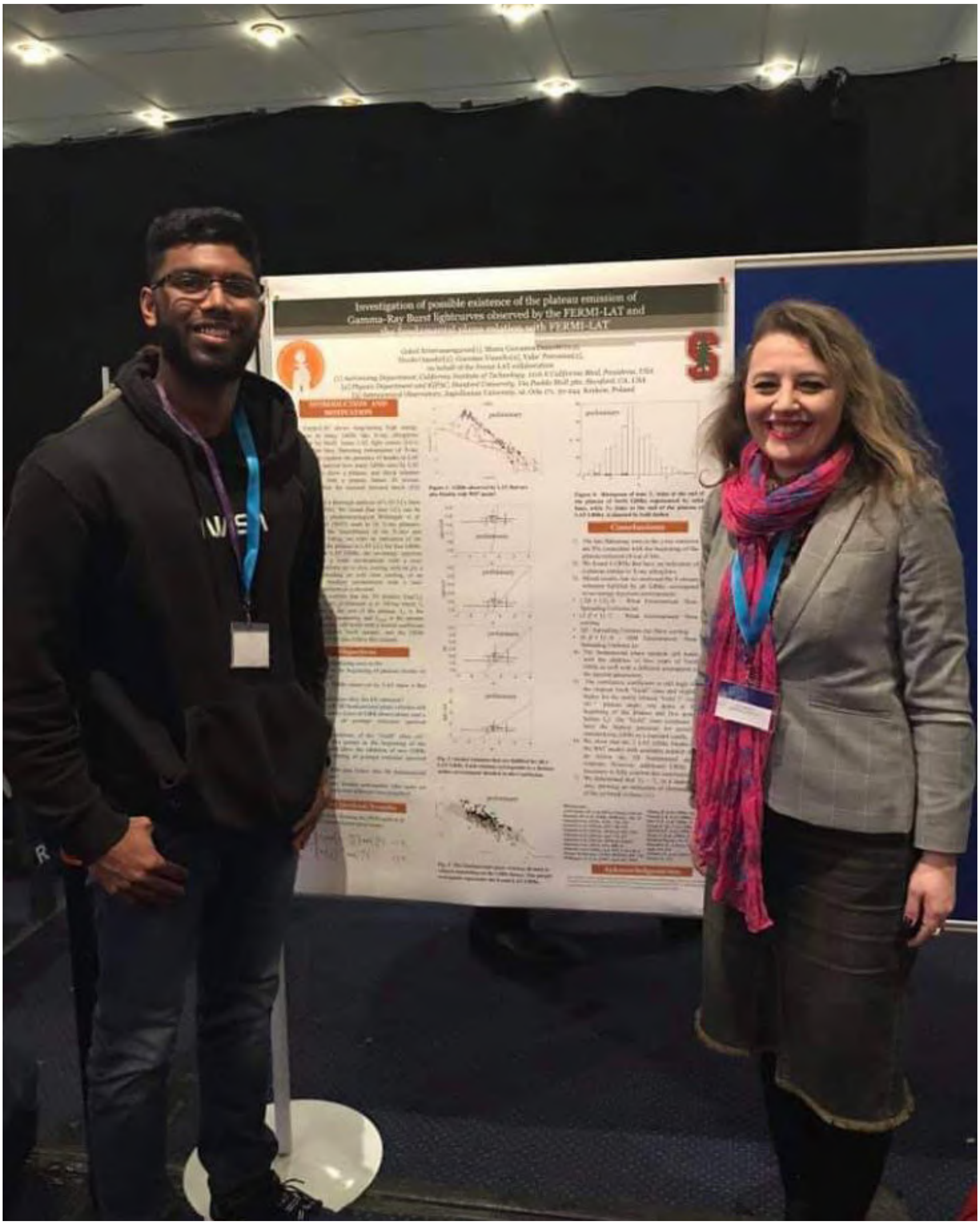
Using a set of theoretical relationships which link the temporal decay phase in the "afterglow" part of the light curve and the GRBs' spectral signatures in the same part of the light curve, the team was able to determine whether a majority of the GRBs in their data sample were produced in a constant-density interstellar medium (ISM) environment, or in a "wind" ejected by the GRB progenitor which decreases with distance.

Next they revisited the 3D Fundamental Plane with the information about GRB environments in hand and discovered that GRBs falling under a fast-cooling regime (the name given to the class of GRBs which exhibit a rapid cool-down of emitted electrons relative to the synchrotron radiation from the burst) lie the closest to the 3D Fundamental Plane—no matter whether the GRB was produced in a constant-density or wind environment. Indeed, the closer GRBs are to the plane, the more precisely they serve as standard candles.

Before this paper, Dr. Dainotti and her collaborators searched for a standard set of GRBs selected by segregating observational classes—this is the first time that the standard set comes naturally from assuming a particular theory.

Thus, the team demonstrated that this new method of classifying GRBs through their astrophysical environments and cooling regimes is the key to potentially enabling astrophysicists to use GRBs as standard candles.

“The story of the 3D Fundamental Plane does not end here,” Dainotti says. “We will continue matching theory and observations, by exploring the region of the plateau itself, since here we have investigated the region after the plateau. The final step will be the application of this 3D relation to obtain cosmological parameters such as the density of matter in the Universe, but at much larger distances.”



Gokul Srinivsaragavan and Maria Dainotti in front of a poster detailing their research. (Photo courtesy M. Dainotti.). Dainotti and sharing first author credit is Gokul Srinivasaragavan, a senior at the California Institute of Technology who spent two summers at the SLAC National Accelerator Laboratory and Stanford University with mentor Dr. Dainotti through the Science Undergraduate Laboratory Internships (SULI) program.

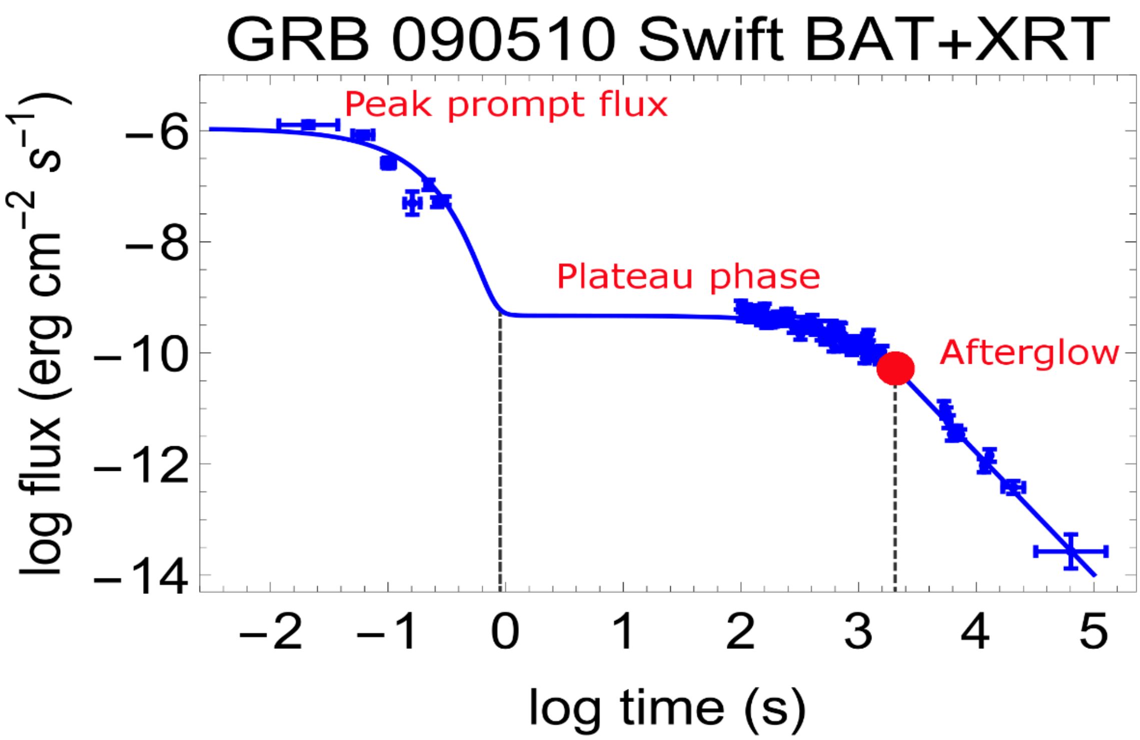


Figure 1.

The light curve of GRB 090510 with the Willingale et al. 2007 function in blue superimposed and the regions of prompt, plateau and afterglow indicated. (Credit: Srinivasaragavan, Dainotti, et al. (2020).)

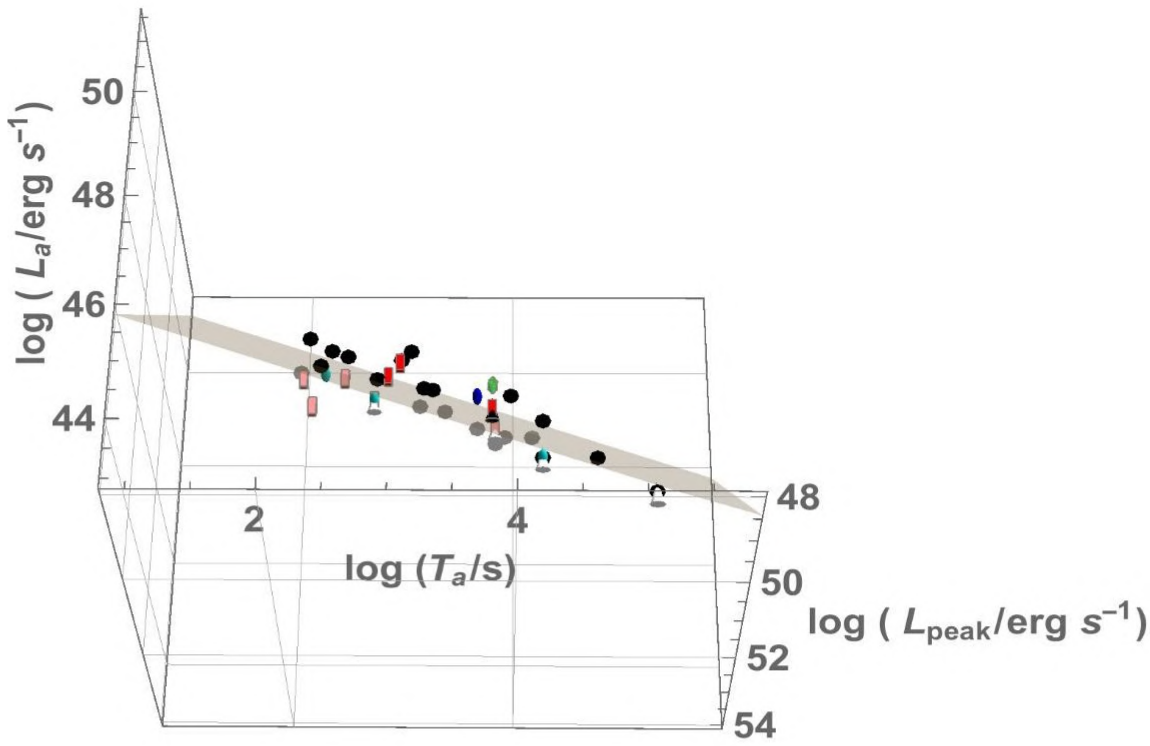


Figure 2.

The La-Ta-Lpeak relation for the "Wind Fast Cooling" sample for the various classes of GRBs which presents the best fit to the plane. Red rectangles indicate short-duration GRBs, black circles indicate long-duration GRBs, and white cones mark GRBs for which the associated SNe type Ib/c have been observed. Note that most of these GRBs are falling now near the GRB 3D Fundamental Plane. (Credit: Srinivasaragavan, Dainotti, et al. (2020).)