Constraining Natal Kicks of Binary Neutron Star Systems

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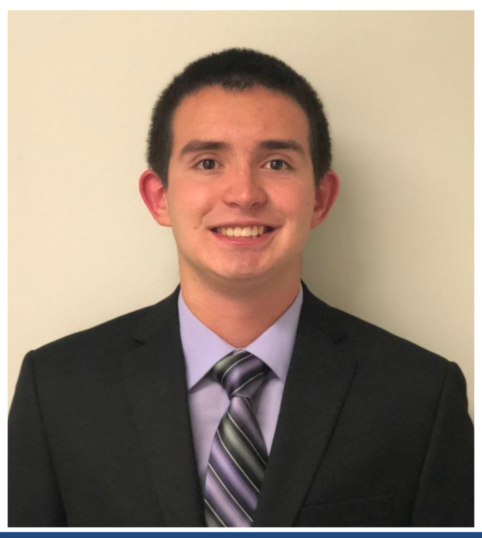
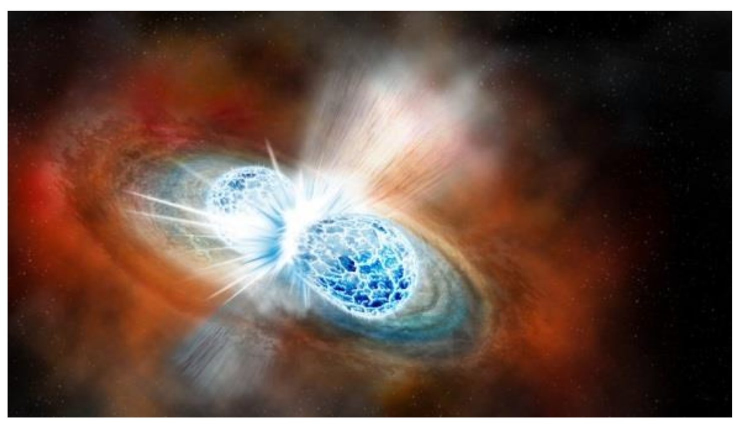


Detection of Short Gamma-Ray Bursts from Binary Neutron Star Systems

On August 17, 2017, The Laser Interferometer Gravitational-Wave Observatory (LIGO) detected gravitational waves from a binary neutron star (BNS) merger. This event was the first piece of definitive evidence connecting neutron star mergers as the source of short gamma-ray bursts (sGRBs) (Abbott et al. 2017a), (Abbott et al. 2017b).



On the left is artist's rendition of a BNS merger. Prior to the merger, energy from the system is given off in the form of gravitational waves, causing the stars to spiral inwards until they finally collide, emitting light across the electromagnetic spectrum.

Do Different Natal Kick Magnitudes Cause Mergers in Different Locations?

BNS mergers that occur outside of their host galaxies may require a velocity kick from the supernova explosion that birthed them. The magnitudes of these natal kicks are highly uncertain, but observations of such merging BNS systems can heighten our understanding of them and supernova physics in general. In this project, we focus on simulating the particular BNS system corresponding to GRB 070809, which is highly offset from its massive elliptical host galaxy, to constrain aspects of the system's progenitor.

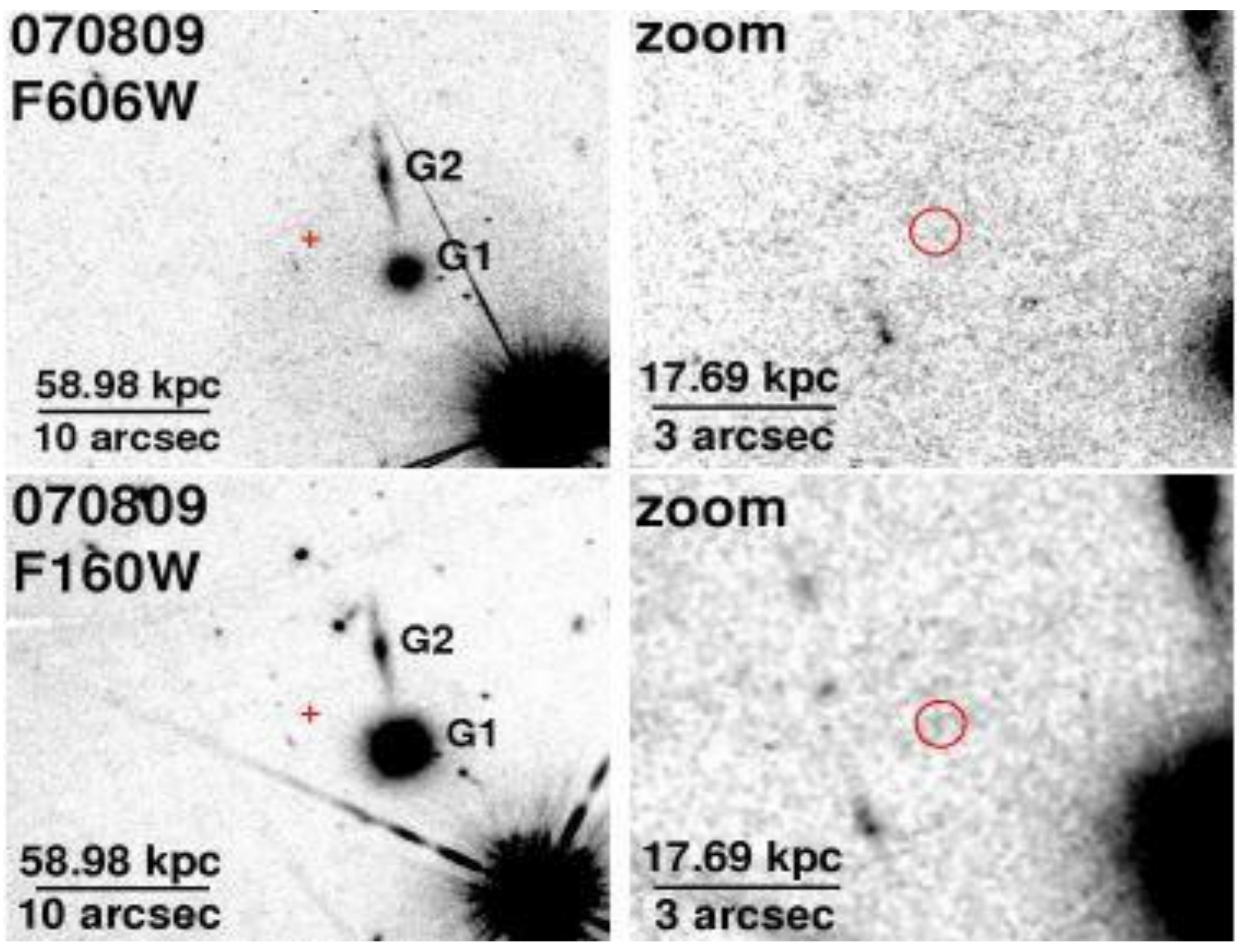


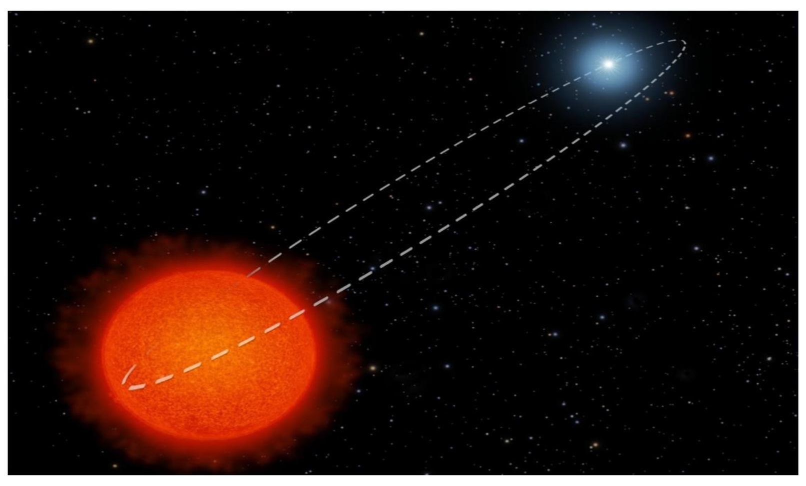
Figure 1. Shown above is an image from the *Hubble Space Telescope* depicting the afterglow position of GRB 070809, represented by the red cross and the red circle. G1 and G2 are the most probable and second most probable host galaxies, respectively (Fong & Berger 2013).

Searching for sGRB Analogs

We sample various input parameters in order to simulate BNS systems from supernova to merger. The motion of the systems following the supernova is consequent of the following parameters: the mass of the second helium star prior to supernova (M_{He}); the semi-major axis of the system's orbit prior to supernova (A_{pre}); the birth radius of the system in its host galaxy (R_{Birth}); and the natal velocity kick (see Hobbs et al. 2005 and references therein) resulting from the supernova (V_{Kick}). We use the following initial conditions, then examine the recovered natal kick distributions and search for sGRB analogs by applying the constraint that the system must merge at the correct observed projected offset from its host galaxy.

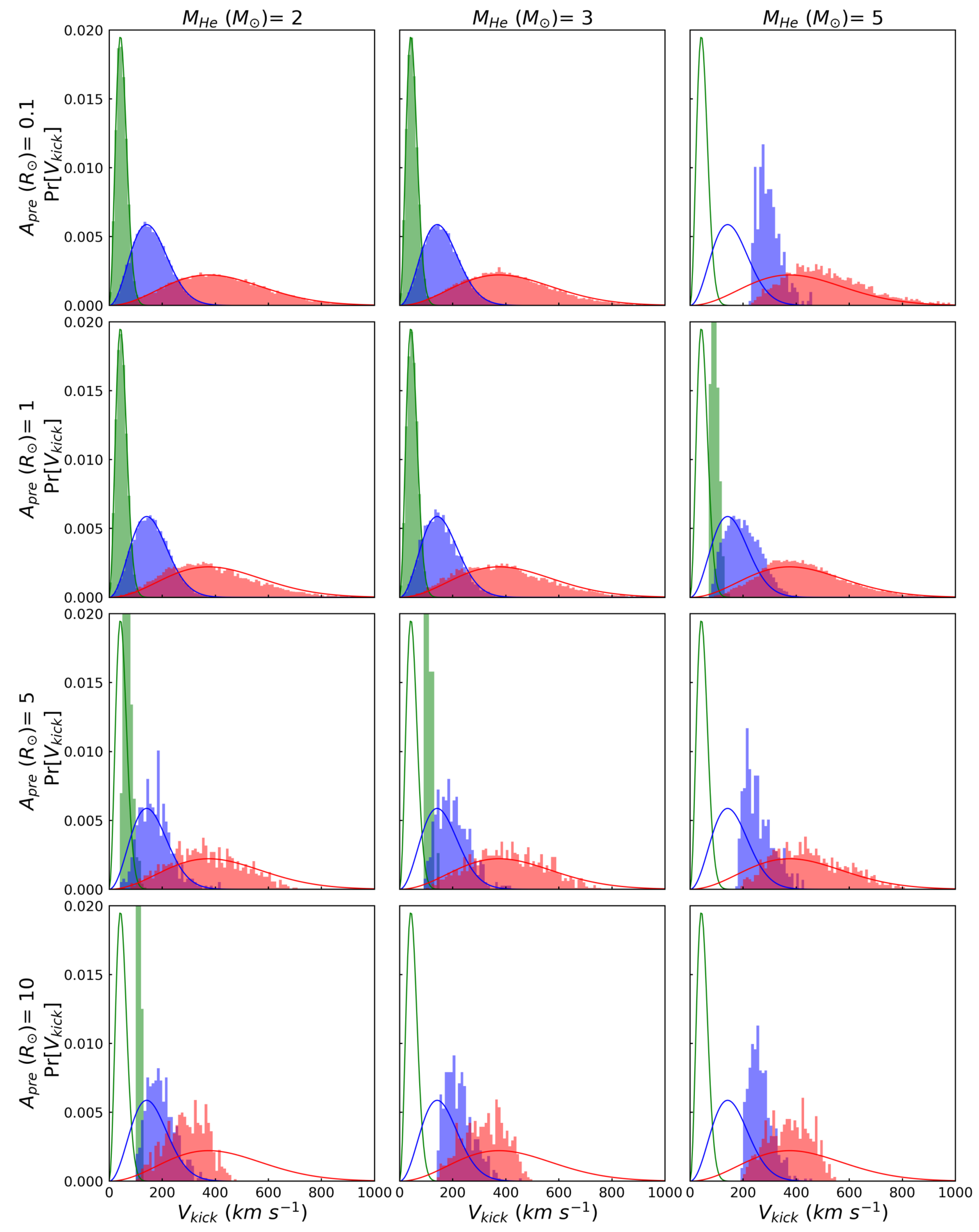
- M_{He} – 2, 3, 5 solar masses
- A_{Pre} – 0.1, 1, 5, 10 solar radii
- V_{Kick} – sampled from Maxwellian distributions with scale factors of 30, 100, and 265

On the right is an artist's rendition of a binary star system with a compact object as one component. M_{He} would correspond to the mass of the red star in this image. A_{Pre} would correspond to the distance from the center of the ellipse shown in white out to one of the stars.



Plotting Short Gamma-Ray Burst Analogs

sGRB Analogs to GRB 070809 by V_{Kick}



sGRB Analogs to GRB 070809 by V_{Kick} (R_{Birth} < 5 Times Effective Radius of Host Galaxy)

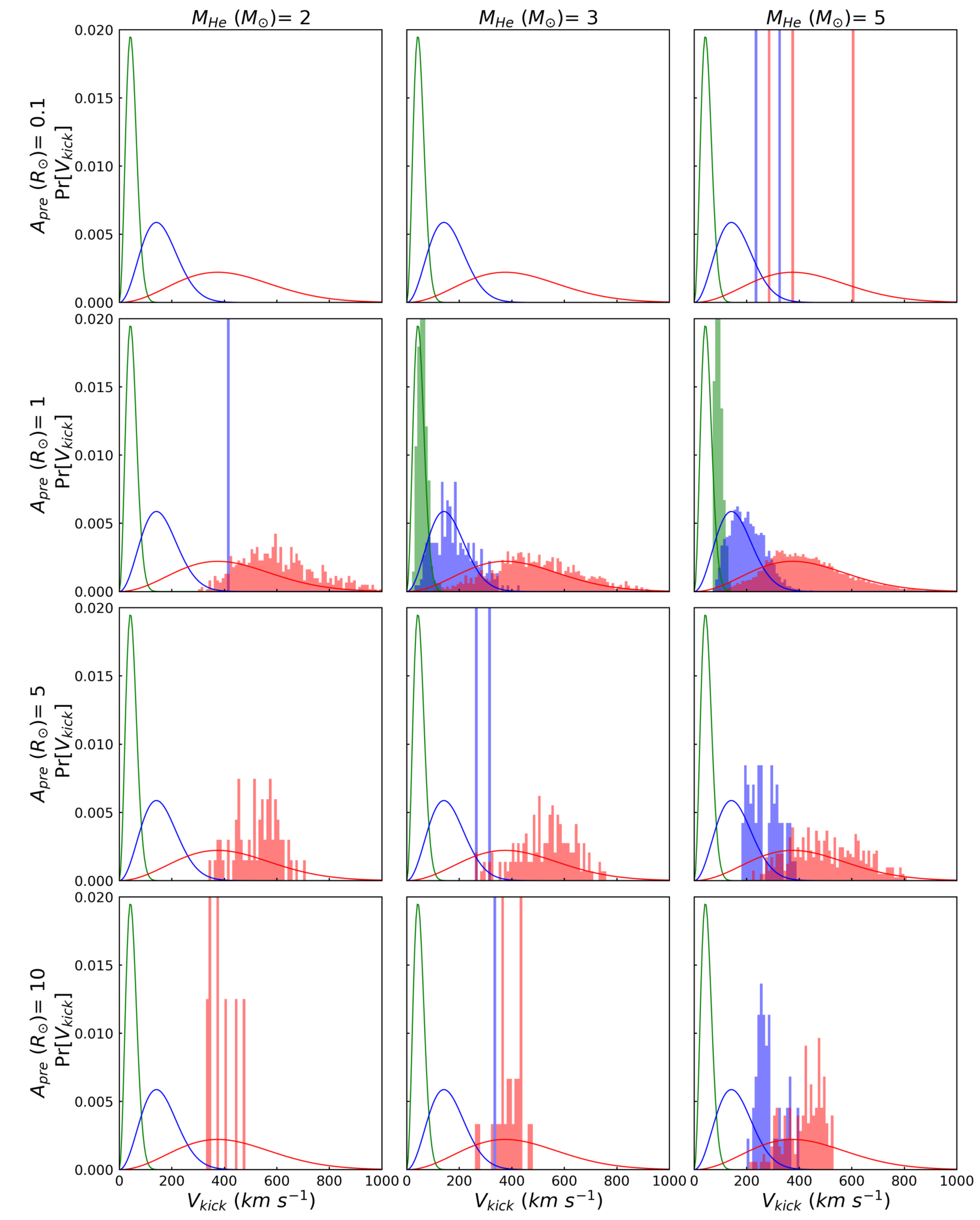
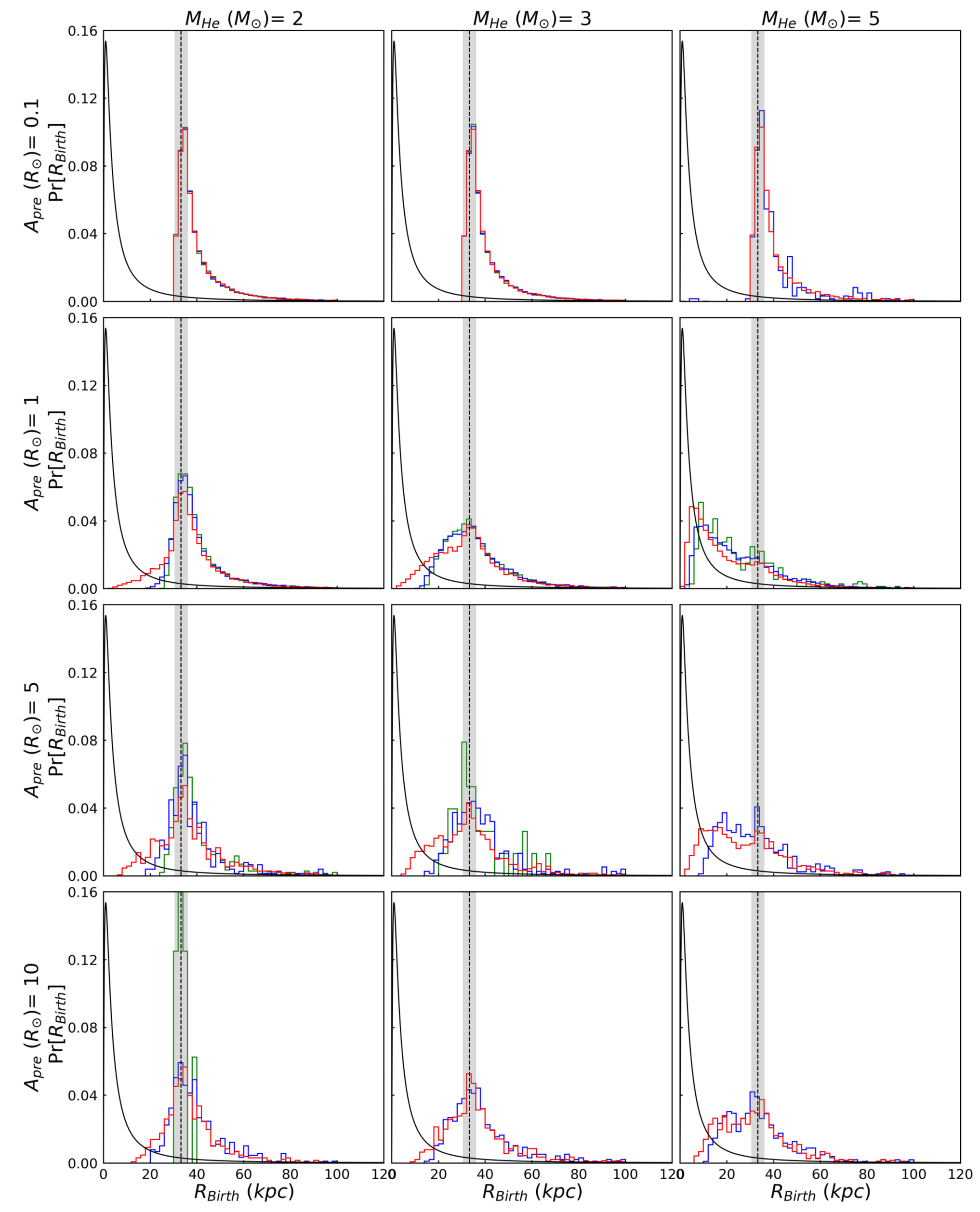


Figure 2. Each plot corresponds to a specific value of A_{Pre} and M_{He}. The histograms show the output probabilities of attaining an sGRB analog at the given V_{Kick} with no constraints on R_{Birth}. Each color corresponds to a different value for the input Maxwellian distribution. The smooth curves represent the actual Maxwellian input distributions.

Maxwellian with σ=30
Maxwellian with σ=100
Maxwellian with σ=265
sGRB Analogs with σ=30
sGRB Analogs with σ=100
sGRB Analogs with σ=265

Figure 3. Same as Figure 2, with R_{Birth} < 5 times the effective radius of the host galaxy. This is a valid assumption since star formation is expected to occur near the centers of such massive elliptical galaxies, whereas the stellar populations in the halos are extremely old.

sGRB Analogs to GRB 070809 by R_{Birth}



PDF for Hernquist Profile
Projected Offset of GRB
Error on Projected Offset
sGRB Analogs with σ=30
sGRB Analogs with σ=100
sGRB Analogs with σ=265

Figure 4. Here, the histograms show the output probabilities of attaining an sGRB analog at the given R_{Birth}. The black dotted line represents the projected offset of GRB 070809, with grey being its error. The black solid line represents the probability density function for the Hernquist profile. Each color corresponds to a different value for the input Maxwellian distribution.

Output Distribution Patterns for sGRB Analogs

Before constraining R_{Birth} of the sGRB analogs, we see that the output distributions of V_{Kick} mostly mirror the input distributions for small values of A_{Pre} and M_{He}. However, we see a cutoff for the maximum allowed V_{Kick} as A_{Pre} increases because a large V_{Kick} is likely to unbound the system, as the stars are already relatively far apart. For higher M_{He} values, we see a minimum cutoff on V_{Kick} which is a result of the interplay with the mass loss. These constraints are determined by the system's survival necessity after the supernova, not the offset.

After we apply the constraint that R_{Birth} be less than 5 times the effective radius (half-light radius) of the galaxy, we see a drop in the overall number of sGRB analogs, though they are still concentrated near the input distributions. Now, we see that in almost every plot, higher values of V_{Kick} are required to create sGRB analogs. However, for the row where A_{Pre} = 1, we see a wide range of supported V_{Kick}s. This shows that small V_{Kick}s are capable of producing systems that travel great distances before merging, though this is an infrequent event. It is worth noting that there are virtually no systems that meet the R_{Birth} constraint and survive under the A_{Pre} = 0.1 column. This shows that if the system starts too close together, it will not have enough time to reach the projected offset of the sGRB.

In the plot of R_{Birth}, we see most sGRB analogs centered around the projected offset of GRB 070809. However, stellar population data suggests concentrations should be under Hernquist profiles.

Conclusions and Going Forward

In general, we saw a wide range of allowed natal kicks that produce sGRB analogs. For almost all kick models, we need V_{Kick}s that exceed 100 km/s to explain the observed offset, and V_{Kick}s exceeding 900 km/s are allowed by the data. Constraining R_{birth} shows that it is difficult for a system to form within the central regions of its host galaxy and travel a great distance before merging. Most systems that became sGRB analogs actually had an R_{birth} near the projected offset of the sGRB, which does not agree with stellar population data. In the future, we can run the same simulations on different sGRB's. Running simulations on sGRB's with greater/shorter merge distances and other different factors will yield different recovered natal kick distributions.

Acknowledgments and References

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