Mergers of Charged Black Holes: Gravitational Wave Events, Short Gamma-Ray Bursts, and Fast Radio Bursts

Bing Zhang

[1]*Department of Physics and Astronomy, University of Nevada Las Vegas, NV 89154, USA*

The discovery of GW 150914 suggests that double black hole (BH-BH) mergers are common in the universe and are the dominant population of the detectable gravitational wave events[1]. Unlike double neutron star (NS-NS) mergers and black hole - neutron star (BH-NS) mergers that are believed to be accompanied with rich electromagnetic (EM) counterparts[2–9], the BH-BH merger systems are not expected to have copious surrounding materials to power bright EM counterparts due to accretion. However, the Fermi GBM team surprisingly detected a putative short gamma-ray burst 0.4 seconds after the GW chirp signal[10]. On the other hand, at least some fast radio bursts (FRBs), mysterious milliseconds-duration radio transients[11,12], are recently identified to have a cosmological origin[13], but their physical origin remains unknown. Here I show that if at least one of the two merging black holes carries a small amount of charge, the inspiral of the BH-BH system would drive a magnetic dipole normal to the orbital plane. A magnetosphere would be developed, and the system would behave like a giant pulsar with increasing wind power. The magnetospheric activities during the final merging phase would make an FRB if the BH charge can be as large as a factor of $\hat{q} \sim 10^{-6}$ of the critical charge Q_c of the BH. At large radii outside the magnetosphere, dissipation of the Poynting flux energy in the outflow would power a short duration high-energy transient, which would

appear as a detectable short GRB if the charge can be as large as $\hat{q} \sim 10^{-4}$. The putative short GRB coincident with GW 150914 can be interpreted with this model. Future joint GW - GRB - FRB searches would verify this model and lead to measurements or constraints on the charges carried by isolate black holes.

Black holes (BHs) are uniquely described with three parameters, mass M, angular momentum J, and charge Q. Whereas the first two parameters have been measured with various observations for both stellar-mass and super-massive BHs, it has been widely believed that the Q parameter must be very small, since opposite charges tend to neutralize any possible net charges of a BH. Nonetheless, the possibility of a small amount of Q in isolated BHs is not impossible, and even likely[14]. However, no measurement or upper limit of Q has been made for any BH.

Recently, the Laser Interferometer Gravitational-wave Observatory (LIGO) team announced the ground-breaking discovery of the first gravitational wave (GW) source, GW 150914, which is a BH-BH merger with two BH masses $36^{+5}_{-4}M_\odot$ and $29^{+4}_{-4}M_\odot$, respectively[1]. Very intriguingly and surprisingly, the *Fermi* GBM team reported a 1-second long weak gamma-ray burst (GRB) 0.4 seconds after the GW event was detected[10].

A non-rotating, charged BH can be described by the Reissner-Nordström (RN) metric

$$ds^2 = \left(1 - \frac{r_s}{r} + \frac{r_Q^2}{r^2}\right) c^2 dt^2 - \left(1 - \frac{r_s}{r} + \frac{r_Q^2}{r^2}\right)^{-1} dr^2 r^2 (d\theta^2 + \sin^2\theta d\phi^2), \qquad (1)$$

where

$$r_s = \frac{2GM}{c^2}, \;\; r_Q = \frac{\sqrt{G}Q}{c^2} \qquad (2)$$

are the Schwarzschild radius and the RN radius, respectively, M, Q are the mass and charge of the black hole, G and c are the gravitational constant and speed of light, respectively, and the electrostatic cgs units have been used. By equating r_s and r_Q, one may define a characteristic charge

$$Q_c \equiv 2\sqrt{G}M = (1.0 \times 10^{31} \text{ e.s.u.}) \left(\frac{M}{10M_\odot}\right), \tag{3}$$

which is $(3.3 \times 10^{21} \text{ C})$ $(M/10M_\odot)$ in the S.I. units. The charge of this magnitude would significantly modify the space-time geometry with a magnitude similar to M. We consider a BH with a charge

$$Q = \hat{q}Q_c, \tag{4}$$

with the dimensionless parameter $\hat{q} \ll 1$. For simplicity, in the following we consider two identical BHs with the same M and Q.

As the two BHs revolve with the Keplerian speed (the general relativistic effect is neglected for an order-of-magnitude estimate), a circular current loop forms, which has a magnetic dipole moment

$$\mu = \frac{\pi I(a/2)^2}{c} = \frac{\sqrt{2GMa}Q}{4c} = \frac{\sqrt{2}G^{3/2}M^2}{c^2}\hat{q}\hat{a}^{1/2} = (1.1\times10^{33} \text{ G cm}^3) \left(\frac{M}{10M_\odot}\right)^2 \hat{q}_{-4}\hat{a}^{1/2}, \tag{5}$$

where $I = 2Q/P$ is the current,

$$P = \frac{2\pi}{\sqrt{2GM}}a^{3/2} = 8\sqrt{2}\pi\frac{GM}{c^3}\hat{a}^{3/2} = (1.7 \text{ ms}) \left(\frac{M}{10M_\odot}\right) \hat{a}^{3/2} \tag{6}$$

is the Keplerian orbital period, $a = \hat{a}(2r_s)$ is the separation between the two BHs, and $\hat{a}$ is the distance normalized to $2r_s$. Notice that $\hat{q}$ is normalized to 10^{-5}, suggesting that even a small amount of charge can induce a large enough magnetic dipole. For comparison, a magnetar with surface magnetic field $B_p \sim 10^{15}$ G has a magnetic dipole $\mu_{\rm mag} \sim B_p R^3 = (10^{33}~{\rm G~cm^3}) B_{p,15} R_6^3$.

This magnetic dipole aligns with the spin axis of the system. Similar to pulsars, unipolar induction due to the rapid rotation of the system would develop strong voltages across different field lines. The curvature of the field lines and especially the general relativistic effect[15–17] would cause depletion of charge densities from the Goldreich-Julian density[18] near the polar regions, leading to strong electric field parallel to the field lines ($E_{\parallel}$) in the so-called "gap" region. Background γ-ray photons entering the inner magnetosphere would be converted to e^+e^- pairs, which are accelerated in the opposite directions in the gap[19]. The accelerated charges emit γ-rays via curvature radiation and inverse Compton scattering, which are converted to e^+e^- pairs in the strong magnetic fields and photon field. The pairs radiate more γ-rays via synchrotron radiation and inverse Compton scattering, leading to a full pair-photon cascade[20]. As a result, a magnetosphere is expected to be developed long time before the final coalescence, with a strong outflow or a magnetospheric wind launched[21,22]. The power of the wind is of the order of the dipole radiation power[23–25], i.e.

$$L_w \simeq \frac{2\mu^2\Omega^4}{3c^3} = \frac{c^5}{768G}\hat{q}^2\hat{a}^{-5} \simeq (4.7\times 10^{48}~{\rm erg~s^{-1}})\hat{q}_{-4}^2\hat{a}^{-5}. \tag{7}$$

Notice that this wind power does not depend on the BH mass M, and *is determined by fundamental constants and the dimensionless parameters $\hat{q}$ and $\hat{a}$ only*. A small amount of charge with $\hat{q} \sim (10^{-5} - 10^{-4})$ is adequate to make a transient with the power of a GRB.

The light cylinder radius of the magnetosphere $r_{\rm LC} = cP/2\pi$ rapidly shrinks with time. Also normalized to $2r_s$, one has

$$\hat{r}_{\rm LC} = \sqrt{2}\hat{a}^{3/2}, \quad \text{or} \quad \frac{\hat{r}_{\rm LC}}{\hat{a}} = \sqrt{2\hat{a}}. \tag{8}$$

At the final stage of coalescence ($\hat{a} \sim 1$), one has $\hat{r}_{\rm LC}/\hat{a} \sim \sqrt{2}$, suggesting a *nearly isotropic* outflow.

Another interesting behavior is that the power is very sensitive to $\hat{a}$, with the power increasing rapidly as the orbital separation shrinks. The highest power happens right before the final merger, so that it produces an *fast radio burst* and a *short-duration γ-ray burst*. One may estimate the time scale for the orbital separation to shrink from $\hat{a} = 2$ to $\hat{a} = 1$, during which L_w increases by a factor of 32. This is

$$\tau_{21} \lesssim \frac{P}{|\dot{P}|} = \frac{20}{3}\frac{GM}{c^3}\hat{a}^4 \simeq (5.2 \text{ ms}) \left(\frac{M}{10M_\odot}\right)\left(\frac{\hat{a}}{2}\right)^4, \tag{9}$$

where

$$\dot{P} = -\frac{192\pi}{5c^5}\left(\frac{2\pi G}{P}\right)^{5/3} f(e)\frac{M^2}{(2M)^{1/3}} \simeq \frac{6\sqrt{2}\pi}{5}\hat{a}^{-5/2} \tag{10}$$

is the orbital decay rate for GW radiation[26], with $f(e) \simeq 1$ for $e \simeq 0$ (which is the case before the final coalescence).

This time scale (Eq.(9)) places an upper limit of the duration of an observable FRB. Similar to radio pulsars, the FRB emission can be produced via coherent "bunching" curvature radiation mechanism by the pairs streaming out from the magnetosphere. For a dipolar magnetic field, a field line in spherical coordinate is delineated as $r = r_e \sin^2\theta$, where $r_e = \xi r_{\rm LC}$, with $\xi > 1$ for open field lines. For the very wide fan beam we are considering ($r \sim r_e$), the curvature radius for a dipolar field configuration is $\rho \sim (0.3-0.6)r_e$ in a wide range of r. Setting $\rho \sim 0.5 r_e \sim (4.2\times 10^6\ \mathrm{cm})\ \hat{a}^{3/2}(M/10M_\odot)\xi$, one can derive the curvature radiation frequency of the pairs

$$\nu = \frac{3}{4\pi}\frac{c}{\rho}\gamma_e^3 \simeq (1.7\times 10^9\ \mathrm{Hz})\ \hat{a}^{-3/2}\left(\frac{M}{10M_\odot}\right)^{-1}\xi^{-1}\gamma_{e,2}^3, \tag{11}$$

where the Lorentz factor of the pairs γ_e is normalized to 100, the nominal value of pairs from polar cap cascade[20]. This frequency is the typical frequency of the observed FRBs. The curvature radiation emission power of an electron is $P_e = \frac{2}{3}\frac{e^2 c}{\rho^2}\gamma_e^4 \simeq (2.6\times 10^{-14}\ \mathrm{Hz})\ \hat{a}^{-3}(M/10M_\odot)^{-2}\xi^{-2}\gamma_{e,2}^4$. For the bunching coherent mechanism[19], the total emission power is $P = N_{\rm bunch}N_e^2 P_e$, where N_e is the number of electrons in each bunch, $N_{\rm bunch}$ is the number of bunches, with the total number of electrons defined by $N_{\rm tot} = N_{\rm bunch}N_e$. The minimum number of electrons that are needed to reproduce the typical luminosity of an FRB, $L_{\rm FRB} = 10^{43}\ \mathrm{erg\ s^{-1}}\ L_{\rm FRB,43}$, is to assume that $N_{\rm bunch} = 1$ and $N_{\rm tot} = N_e$, so that

$$N_{\rm tot,min} = \left(\frac{L_{\rm FRB}}{P_e}\right)^{1/2} \simeq 1.9\times 10^{28}\ \hat{a}^{3/2}\left(\frac{M}{10M_\odot}\right)\xi\gamma_{e,2}^{-2}L_{\rm FRB,43}^{1/2}. \tag{12}$$

The total number of emitting electrons in the magnetosphere may be estimated as

$$N_{\rm tot} \sim r^3\chi n_{\rm GJ} \simeq (4.3\times 10^{34})\chi\left(\frac{M}{10M_\odot}\right)q_{-4}\hat{a}^{-1} \gg N_{\rm tot,min}, \tag{13}$$

suggesting that the bunching mechanism can well operate in such transient magnetospheres to power an observable FRB. Here $n_{\rm GJ} \sim (\Omega B)/(2\pi c e) = \mu/(P c e r^3) \simeq (7.3\times 10^{13}\ \mathrm{cm^{-3}})\ \hat{q}_{-4}(M/10M_\odot)^{-2}\hat{a}^{-11/2}(r/r_{\rm LC})^{-3}$ is the Goldreich-Julian charge number density[18], and χ is the pair multiplicity. Comparing Eq.(7) with the typical FRB luminosity $L_{\rm FRB} \sim 10^{43}\ \mathrm{erg\ s^{-1}}$, one can see that an FRB can be generated if $\hat{q} > 10^{-6}$.

The pair cascade process only converts a small fraction of the wind energy into radiation (radio emission and a weak thermal γ-ray emission component from the photosphere). The dominant energy component in the outflow would be in the form of a Poynting flux. The EM energy is entrained in the outflow and gets dissipated at a large radius through reconnection triggered by internal collision or current instabilities[27,28]. Assuming that gravitational waves (GWs) travel with the speed of light (a prediction of Einstein's Equivalent Principle, which is tightly constrained with the data of GW 150914[29]), the γ-ray emission would be delayed with respect to the GW chirp signal. Suppose the GRB emission starts at radius R_1 with Lorentz factor Γ_1 and ends at radius R_2 with Lorentz factor Γ_2, one can define

$$t_1 = \frac{R_1}{2\Gamma_1^2 c}, \quad t_2 = \frac{R_2}{2\Gamma_2^2 c}. \tag{14}$$

Several observational time scales can be estimated as follows:

- The delay time between the onset of the GRB and the final GW chirp signal is

$$\Delta t_{\rm GRB} \sim (t_1 - \tau_{21})(1+z). \tag{15}$$

- The rise time scale of the GRB is defined by

$$t_r \sim \max(\tau_{21}, t_2 - t_1)(1+z). \tag{16}$$

- The decay time scale of the GRB is defined by

$$t_d \sim t_2(1+z). \tag{17}$$

- The total duration of the GRB is

$$\tau = t_r + t_d. \tag{18}$$

The putative GRB associated with GW 150914[10] has a duration $\tau \sim 1$ s, and was delayed with respect to the GW signal by $\Delta t_{\rm GRB} \sim 0.4$ s. Assuming the redshift of GW 150914[1], $z = 0.09^{+0.03}_{-0.04}$, the 1 keV - 10 MeV luminosity of the putative GRB is $1.8^{+1.5}_{-1.0} \times 10^{49}$ erg s^{-1}. According to Eq.(7), one can estimate the charge of the BHs as

$$\hat{q}_{-4} \simeq 1.9 \eta_\gamma^{-1/2}, \tag{19}$$

where $\eta_\gamma = L_\gamma / L_w$ is the radiative efficiency of the GRB. The delay and the short duration of the GRB are also readily explained. According to Eq.(9), approximating $M \sim 30 M_\odot$ for both BHs in GW 150914, one may estimate $\tau_{21} \lesssim 15$ ms, which is $\ll$ the delay time $\Delta t_{\rm GRB} \sim 0.4$ s. One therefore has $t_{\rm GRB} \sim t_1$ (noticing $(1+z) \sim 1$), which gives a constraint on the onset radius of emission

$$R_1 \sim 2\Gamma_1^2 c t_{\rm GRB} = (2.4 \times 10^{14}\ {\rm cm}) \left(\frac{\Gamma_1}{100}\right)^2 \left(\frac{\Delta t_{\rm GRB}}{0.4\ {\rm s}}\right). \tag{20}$$

The weak signal does not allow a precise measurement of t_r and t_d. In any case, the pulse is asymmetric[10] with $t_d = t_2 \gg t_r = t_2 - t_1$, consistent with the theory. The total duration $\tau = 2t_2 - t_1 \sim t_2$, which defines the decay time scale due to the angular spreading curvature effect. One can then estimate the radius where emission ceases, i.e.

$$R_2 \sim 2\Gamma_2^2 c t_2 \sim 2\Gamma_2^2 c \tau = (6.0 \times 10^{14}\ {\rm cm}) \left(\frac{\Gamma_2}{100}\right)^2 \left(\frac{\tau}{1\ {\rm s}}\right). \tag{21}$$

Even though the Lorentz factor Γ for such kind of GRBs is unknown, we can see that for nominal values ($\Gamma_1 \sim \Gamma_2 \sim 100$) of known GRBs, the emission radius is much greater than the photosphere radius, suggesting that the GRB emission comes from an optically thin region. The large radius is consistent with the expectation of the models that invoke magnetic dissipation in a Poynting flux dominated outflow[27,28].

Since the minimum required $\hat{q}$ for FRBs (10^{-6}) is two orders of magnitude smaller than that required for an observable short GRB (10^{-4}), one would expect that there are more associations of BH-BH mergers with FRBs than GRBs. If all BHs have $\hat{q}$ at least 10^{-6}, then essentially all BH-BH mergers would be accompanied with FRBs, and only a small fraction, i.e. those with $\hat{q}$ as large as 10^{-4} would make observable short GRBs. The inferred event rate density of BH-BH mergers from the detection of GW150914[30] is $\sim (2-53)\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$, with the most optimistic value as high as $\sim 400\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$. The FRB event rate density may be estimated as

$$\dot{\rho}_{\mathrm{FRB}} = \frac{365\dot{N}_{\mathrm{FRB}}}{(4\pi/3)D_{\mathrm{L}}^3} \simeq 720\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}\ \left(\frac{d_{\mathrm{L}}}{6.7\ \mathrm{Gpc}}\right)^{-3} \left(\frac{\dot{N}_{\mathrm{FRB}}}{2500}\right), \tag{22}$$

where $\dot{N}_{\mathrm{FRB}}$ is the daily all-sky FRB rate which is normalized to 2500[31], and D_{L} is the luminosity distance of the FRB normalized to 6.7 Gpc ($z = 1$). The most optimistic BH-BH merger rate is still about a factor of (2-14) times smaller than the estimated FRB event rate. The discrepancy can be resolved by considering more than one progenitor systems for FRBs, and that FRB-150418-like events are only a small fraction of the entire FRB population[13,32].

In summary, according to the theoretical picture delineated in this work, one makes the following predictions: Most, if not all, BH-BH mergers are associated with FRBs of $\hat{q}$ of isolated BHs can be as large as 10^{-6}. A fraction (those with $\hat{q}$ as large as 10^{-4}) would make an observable short GRB. Due to the smaller emission radius of the FRB emission, the FRB time essentially coincides with the GW chirp signal, whereas the short GRB should be slightly delayed with respect to the chirp signal, as is the case of GW 150914-associated GBM event[10]. FRB 150418 has a radio afterglow with brightness comparable to that of a short GRB[13]. This is fully consistent with this picture. A coordinated search for associated GW, GRB and FRB events among the GW, γ-ray, and radio communities is greatly encouraged to pin down the origins of FRBs and to measure the charges of isolated merging BHs.

1. Abbott, B. P. *et al.* Observation of Gravitational Waves from a Binary Black Hole Merger. *Physical Review Letters* **116**, 061102 (2016). 1602.03837.

2. Paczýnski, B. Gamma-ray bursters at cosmological distances. *ApJ* **308**, L43–L46 (1986).

3. Eichler, D., Livio, M., Piran, T. & Schramm, D. N. Nucleosynthesis, neutrino bursts and gamma-rays from coalescing neutron stars. *Nature* **340**, 126–128 (1989).

4. Paczýnski, B. Cosmological gamma-ray bursts. *Acta Astronomica* **41**, 257–267 (1991).

5. Narayan, R., Paczynski, B. & Piran, T. Gamma-ray bursts as the death throes of massive binary stars. *ApJ* **395**, L83–L86 (1992). arXiv:astro-ph/9204001.

6. Mészáros, P. & Rees, M. J. High-entropy fireballs and jets in gamma-ray burst sources. *MNRAS* **257**, 29P–31P (1992).

7. Rezzolla, L. *et al.* The Missing Link: Merging Neutron Stars Naturally Produce Jet-like Structures and Can Power Short Gamma-ray Bursts. *ApJ* **732**, L6 (2011). 1101.4298.

8. Li, L.-X. & Paczyński, B. Transient Events from Neutron Star Mergers. *ApJ* **507**, L59–L62 (1998). `arXiv:astro-ph/9807272`.

9. Metzger, B. D. *et al.* Electromagnetic counterparts of compact object mergers powered by the radioactive decay of r-process nuclei. *MNRAS* **406**, 2650–2662 (2010). `1001.5029`.

10. Connaughton, V. *et al.* Fermi GBM Observations of LIGO Gravitational Wave event GW150914. *ArXiv e-prints* (2016). `1602.03920`.

11. Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J. & Crawford, F. A Bright Millisecond Radio Burst of Extragalactic Origin. *Science* **318**, 777– (2007). `0709.4301`.

12. Thornton, D. *et al.* A Population of Fast Radio Bursts at Cosmological Distances. *Science* **341**, 53–56 (2013). `1307.1628`.

13. Keane, E. F. *et al.* The host galaxy of a fast radio burst. *Nature* **530**, 453–456 (2016). `1602.07477`.

14. Ruffini, R., Vereshchagin, G. & Xue, S.-S. Electron-positron pairs in physics and astrophysics: From heavy nuclei to black holes. *Physics Reports* **487**, 1–140 (2010). `0910.0974`.

15. Arons, J. & Scharlemann, E. T. Pair formation above pulsar polar caps - Structure of the low altitude acceleration zone. *ApJ* **231**, 854–879 (1979).

16. Muslimov, A. G. & Tsygan, A. I. General relativistic electric potential drops above pulsar polar caps. *MNRAS* **255**, 61–70 (1992).

17. Harding, A. K. & Muslimov, A. G. Particle Acceleration Zones above Pulsar Polar Caps: Electron and Positron Pair Formation Fronts. *ApJ* **508**, 328–346 (1998). `astro-ph/9805132`.

18. Goldreich, P. & Julian, W. H. Pulsar Electrodynamics. *ApJ* **157**, 869 (1969).

19. Ruderman, M. A. & Sutherland, P. G. Theory of pulsars - Polar caps, sparks, and coherent microwave radiation. *ApJ* **196**, 51–72 (1975).

20. Zhang, B. & Harding, A. K. Full Polar Cap Cascade Scenario: Gamma-Ray and X-Ray Luminosities from Spin-powered Pulsars. *ApJ* **532**, 1150–1171 (2000). `astro-ph/9911028`.

21. Usov, V. V. Millisecond pulsars with extremely strong magnetic fields as a cosmological source of gamma-ray bursts. *Nature* **357**, 472–474 (1992).

22. Usov, V. V. On the Nature of Nonthermal Radiation from Cosmological Gamma-Ray Bursters. *MNRAS* **267**, 1035–+ (1994). `arXiv:astro-ph/9312024`.

23. Harding, A. K., Contopoulos, I. & Kazanas, D. Magnetar Spin-Down. *ApJ* **525**, L125–L128 (1999). `astro-ph/9908279`.

24. Xu, R. X. & Qiao, G. J. Pulsar Braking Index: A Test of Emission Models? *ApJ* **561**, L85–L88 (2001). `astro-ph/0108235`.

25. Contopoulos, I. & Spitkovsky, A. Revised Pulsar Spin-down. *ApJ* **643**, 1139–1145 (2006). `astro-ph/0512002`.

26. Taylor, J. H. & Weisberg, J. M. Further experimental tests of relativistic gravity using the binary pulsar PSR 1913 + 16. *ApJ* **345**, 434–450 (1989).

27. Zhang, B. & Yan, H. The Internal-collision-induced Magnetic Reconnection and Turbulence (ICMART) Model of Gamma-ray Bursts. *ApJ* **726**, 90 (2011). `1011.1197`.

28. Lyutikov, M. & Blandford, R. Gamma Ray Bursts as Electromagnetic Outflows. *ArXiv Astrophysics e-prints* (2003). `arXiv:astro-ph/0312347`.

29. Wu, X.-F. *et al.* Testing Einstein's Equivalence Principle With Gravitational Waves. *ArXiv e-prints* (2016). `1602.01566`.

30. Abbott, B. P. *et al.* The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914. *ArXiv e-prints* (2016). `1602.03842`.

31. Keane, E. F. & Petroff, E. Fast radio bursts: search sensitivities and completeness. *MNRAS* **447**, 2852-2856 (2015). `1409.6125`.

32. Masui, K. *et al.* Dense magnetized plasma associated with a fast radio burst. *Nature* **528**, 523–525 (2015). `1512.00529`.

Acknowledgements I thank Mitch Begelman, Tong Liu, Peter Mészáros, Daniel Proga, Martin Rees, Z. Lucas Uhm, and Bin-Bin Zhang for helpful comments and/or discussion. This work is partially supported by NASA under an Astrophysics Data Analysis Program (ADAP) and an Astrophsyics Theory Program (ATP) funded to UNLV.