Modeling the Ocean in an Accreting Neutron Star

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Neutron stars provide some of the most extreme physical conditions in the universe, from the super-strong magnetic fields surrounding and threading these stars to the super-nuclear densities in their interiors. Many of these conditions cannot be recreated in the laboratory, making neutron stars an important and unique probe of fundamental physics. X-ray telescopes, such as Chandra and XMM-Newton, have allowed astronomers to make detailed observations of the surface emission from a large number of neutron stars. These observations can reveal a great deal about neutron stars, if the outer layers are accurately modeled. We present models of the ocean in accreting neutron stars–used in tandem with models of the neutron star crust and core and with X-ray observations, our models can potentially place strong constraints on the properties of these layers.

The ocean of an accreting neutron star is composed of carbon and a variety of heavier elements, and is formed by the nuclear burning of the accreted hydrogen and helium at low densities. As it is compressed to higher densities by ongoing accretion, the matter in the ocean eventually solidifies to form the crust. As the matter is compressed further, heat is released through electron captures and pycnonuclear reactions–this "deep crustal heat" flows upward into the ocean and downward into the core.

The ocean of an accreting neutron star can be observed in (at least) two ways: during an X-ray superburst, and about a week after accretion turns off in a transiently accreting neutron star. In a superburst, the carbon near the base of the ocean reaches a critical density and temperature for unstable ignition, whereupon the entire ocean burns in a runaway thermonuclear event. A large portion of the heat flows upward to the surface of the neutron star and is seen as a large X-ray flash lasting nearly a day. In a transiently accreting neutron star, as soon as accretion turns off, the neutron star begins cooling from the outside in, down to the depth of the inner crust. The top of the ocean begins cooling within a day, and the base of the ocean begins cooling after a week—therefore, observations of the change in surface emission with time in the first week of quiescence will probe the neutron star ocean temperature [1].

At the ocean-crust boundary, as the matter transitions from liquid to solid, it also undergoes chemical separation. Numerical simulations of phase transitions in neutron stars [2] have shown that as the ocean mixture solidifies, light elements (charge numbers $Z < 20$) are preferentially left behind in the liquid whereas heavy elements are preferentially incorporated into the solid. Standard models of the outer layers of an accreting neutron star, which do not include chemical separation in the ocean, cannot produce the high carbon densities and temperatures in the ocean that are required for superbursts [3]. Our models help solve both of these problems. We find that the retention of light elements in the liquid acts as a source of buoyancy that drives a continual mixing of the ocean, enriching it substantially in light elements and leading to a relatively uniform composition with depth [4]. Heat is also transported inward to the ocean-crust boundary by this convective mixing (see Figs. 1 and 2).

Cooling of neutron star transients provides an independent way to constrain chemical separation and mixing in the ocean. As the neutron star cools after an accretion episode, the ocean-crust boundary moves upward. We find that this leads to chemical separation, and then convective mixing and inward heat transport, in a manner similar to that during accretion. The inward heat transport cools the outer layers of the ocean rapidly, but keeps the inner layers hot; the result is a sharp drop in surface emission at around a week, followed by a gradual recovery as cooling becomes dominated by the crust (see Fig. 3). Such a dip should be observable in the light curves of these neutron star transients, if enough data is taken at 10 to 100 days after the end of accretion.

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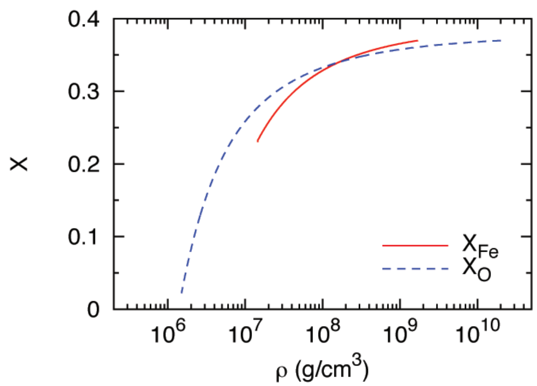

Fig. 1. Composition profile in the convection zone of an ocean composed of iron and selenium (solid red line) and oxygen and selenium (dashed blue line).

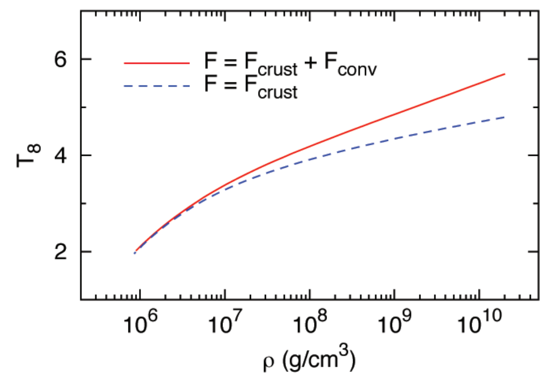

Fig. 2. Thermal profile for an ocean composed of oxygen and selenium, both when the convective flux is included in the total heat flux F (solid red line), and when it is ignored (dashed blue line).

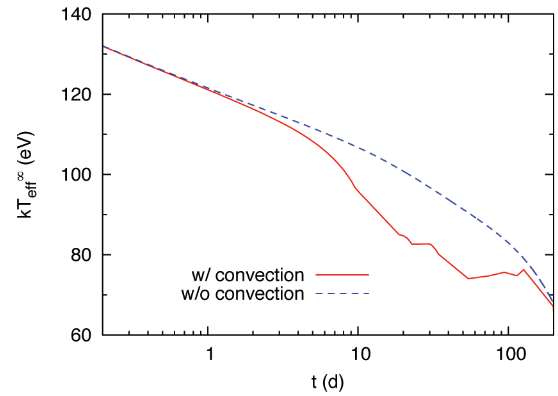

Fig. 3. Example lightcurve during the cooling of a transiently accreting neutron star, both when cooling-induced convection is included (solid red line), and when it is ignored (dashed blue line).

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[3] Cumming, A. et al., *Astrophys J* **646,** 429 (2006).
[4] Medin, Z. and A. Cumming, *Astrophys J* **730,** 97 (2011).

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