Gravity plays a strong role in the propagation of light from the neutron star to observer, as well as on the structure of the neutron star itself. Because of the rapid rotation of millisecond (ms) pulsars, their observed X-ray pulse shapes carry useful information on the mass, radius and surface shape of the neutron star. A numerical model has been developed which includes light bending and time delay effects, as well as Doppler effects for photons. The model also accounts for oblateness of the neutron star caused by the rapid rotation. Scattered light from the surface of the accretion disk is a recent addition to the model. The millisecond pulsar SAX J1808.1-3658 has multiple observations taken during different outbursts. The observed pulse shapes vary greatly, and it is a challenging test to fit the different observations.

Neutron Star EOS and observational constraints

Nuclear Equations of State (EOS)

James Lattimer

EOS determines neutron star structure

One major goal of studying NS: to constrain the EOS of dense matter

Different NS are not on the same radius scale

Pulsations from Magnetic Neutron Stars

Matter is channeled by the magnetic field onto the rotating hot spot

Mis-aligned magnetic field: observer sees pulsations from the rotating hot spot

Path of Light from NS to Observer

• Shadow zone
• Magnification

Doppler effects, time delays and oblateness

The calculation of pulse shapes is done by ray tracing (geodesic equations). We use the numerical general relativity (GR) metric for rotating neutron stars.

Metric calculated with RNS code (Stergioulas, Freedman 1995, based on methods of Komatsu, Einouchi, Machida 1989 and Cook, Shapiro, Teukolsky 1994)

Expansion of the geodesic equations in the metric for a rotating neutron star yields redshift and Doppler factors (Cadeau, Morsink, Leahy & Campbell, 2007)

• Time-delays are important and difference between Schwarzschild and Kerr are not important (Cadeau, Leahy, Morsink 2005)
• Omitting oblateness produces large errors in pulse shapes (B=300 G)(Cadeau, Morsink, Leahy, Campbell 2007)

• An approximation method to the GR method was developed (Morsink, Leahy, Cadeau, Braga 2007) as a practical method calculating pulse shapes

Optical constraints for SAX J1808

• Optical spectroscopy of companion (Cornelisse et al 2009) f(Mc)>0.10 Msun and .051<q<.072, 0.2<Ms<1.6 Msun
• Optical photometry (Deyo et al 2008): 36<δ<67, Mx<2.2 Msun
• Elebert et al 2009: optical spectroscopy: f(Mc)<0.04 Msun 32<δ<74; no good constraint on Mx

Multi-epoch pulse shape modeling

• 7 different pulse shapes (with smallest errors)
• Constant M, R, i (inclination)
• Variable hot spot location
• Introduce scattered x-rays from external material (no doppler or GR effects) with amplitude 1% relative to hot spot

Results

Joint fits with 2-epoch of pulse shapes data are considerably more constraining that those for a single epoch.

Fits using 3 epochs are currently underway and show promise of giving even tighter limits on M and R than obtained already using 2-epoch fits (e.g. see figure just above, here). Results from the 3-epoch fits should be completed in the near future.

We are looking at ways of speeding up the fitting process. With the model including scattered light from the accretion disk, in addition to the spectral model, which fits two energy bands of pulse shape, there are 10, 18, and 26 free parameters for the 1, 2 and 3 epoch fits, respectively. The computation time for the 1 and 2 epoch fits is reasonable, but for the 3 epoch fits (essentially a search in 26 dimensional parameter space), the computation time is becoming a limitation. Joint 4-epoch fits are probably not possible without significant improvements in the parameter space computation.

While current mass-radius constraints from 2-epoch are interesting, they are not yet tight enough to narrow down the allowed EOS as much as needed (see figure above). For 2-epoch fits we hope to reduce the allowed region by a factor ~2 in each case, which will be significantly more constraining. Obtaining and analyzing additional observations of pulse shapes with small statistical errors from millisecond X-ray pulsars is probably the most effective way of improving the constraints.

Summary

Joint fits with 2-epoch of pulse shapes data are considerably more constraining that those for a single epoch.

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