STSM Report - Antonopoulou Danai

1. Purpose of the STSM

The purpose of this visit was to investigate ways in which pulsar rotational 'glitches' (i.e. sudden spin-ups and their subsequent relaxation) can be used to constrain the physics of neutron-star interiors. The main scientific goal was to advance our understanding of the neutron star's core contribution to the glitch phenomenon, especially in view of recent results that the crustal angular momentum reservoir might not be enough to power large spin-ups.

2. Work carried out during the STSM and main results

As a starting point I constructed a comprehensive database, containing all glitches reported to date in the literature (as well as some unpublished events which can be found in Astronomer's telegrams or the Jodrell Bank online glitch catalogue). Using these data I explored possible correlations between the inferred (dipole) magnetic field strength and glitch parameters such as glitching rate and glitch sizes (size of frequency change - absolute $\Delta\nu$ or relative $\Delta\nu/\nu$ and absolute size of spin-down rate change $\Delta\dot{\nu}$). Some trends are observed: high magnetic-field pulsars display somewhat larger spin-down rate changes compared to 'typical' pulsars, but fewer events with large changes in frequency (both in absolute and relative size). The latter could be due to higher internal temperatures as a result of the decay of a stronger magnetic field. A deficiency of small glitches from magnetars and X-ray pulsars is also observed, but is likely due to observational biases since X-ray monitoring is typically less frequent than in the radio band. Despite these trends, there are no statistically significant correlations when the entire glitching pulsar population is examined. I plan to extend this search by looking for correlations within subgroups of neutron stars.

During the STSM I focused mainly on two projects. The first concerns the timing activity of the X-ray pulsar J0537-6910, a project for which it was very beneficial to be based in Southampton and have input from Nils Andersson on the theoretical interpretation of the observations. This pulsar is the fastest young pulsar known and displays an extreme glitching rate (~ 3.5 events per year). Together with my collaborators (C. Espinoza, L. Kuiper and N. Andersson), we analysed all available times of arrival for this source as recorded by the RXTE mission. We found 22 new glitches and measured consistently the total of 45 glitches contained in the data. Glitch searches in simulated datasets were performed in order to optimise the techniques used to characterise the timing and glitch parameters and improve the estimates of the measurement errors. We also examined the long-term spin evolution of this pulsar, which can be described by an 'effective' *negative* braking index. This evolution is shown to be dominated by the discrete changes in spin-down rate at each glitch and subsequent relaxation.

The glitch frequency steps are best described by a wide normal distribution and $\Delta\nu$ strongly correlates with the time interval to the following glitch; a result indicating that glitches in this pulsar are triggered when a critical lag between the superfluid and the normal component is built. A limit for this lag, which is linked to the pinning properties of the crust, was obtained. Another interesting finding of this work is that the magnitudes of the spin-down rate steps correlate with the time interval preceding the glitch. This can be attributed to the decoupling of a superfluid region that has long relaxation timescales. Due to the high glitch rate, such a region has no time to fully re-couple before the occurrence of the next glitch; such a scenario consistently explains the observed correlation and the persisting increase in the spin-down rate which gives rise to the anomalous braking index.

The second project (led by Wynn Ho and in collaboration with C. Espinoza and N. Andersson) concerns a possible technique to measure mass of isolated neutron stars, demonstrating the usefulness of glitch observations as probes of fundamental physics. While the crustal superfluid alone might not be enough to power large glitches as seen e.g. in the Vela pulsar, we show that the moment of inertia of the superfluid region in the S-pairing state (which includes the inner crust and part of the outer core) can act as the required angular momentum reservoir. Observationally, the required moment of inertia was calculated from glitch data of pulsars with a well-defined glitch activity parameter. A subset of pulsars for which internal temperature could be calculated (from their age, by performing cooling simulations) or inferred (from measurements of their surface temperature) was selected. For these sources, we used different models for the superfluid pairing gap to calculate the theoretical moment of inertia of the S-superfluid (as a function of mass). Only one superfluid model can successfully explain all observational data; in turn this allows us to use the observed glitch activity to constrain the mass of each source.

Finally, I began work on a third project - together with S. Lander and N. Andersson from the Gravity Group: investigating the interaction of flux-tubes with neutron vortices which are magnetised due to the (density-dependent) entrainment effect. Using numerical results on magnetic field equilibrium configurations for a type II superconducting core, we will 'map' the vortex pinning strength for various neutron star models. This project is motivated by the observational indications that part of the core's superfluid must be decoupled on longer timescales, to act as a complementary angular momentum reservoir to that of the crust. Our results will enable us to calculate the moment of inertia of such a region and make direct comparisons with glitch observations. Strong pinning in the core however might also impact on the evolution and decay of the magnetic field. I plan to continue my work and collaboration with the Southampton Group members on this project.

3. Forseen publications

1) Ho W.C.G., Espinoza C.M., Antonopoulou D. and Andersson N., *Pinning down the superfluid and measuring masses using pulsar glitches*, submitted
2) Antonopoulou D., Espinoza C.M., Kuiper L. and Andersson N., in preparation
3) Antonopoulou D., Lander S.K. and Andersson N., in preparation