Impact of Internal Heating on the Thermal Evolution of Neutron Stars

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In this work, we have carried out a comparative analysis of the impact of different competing heating processes on the cooling behaviour of neutron stars. In general we find that the internal heating yields significantly enhanced surface temperatures of middle aged and old pulsars, as one would expect. However, the effectiveness of these heating processes varies significantly from one process to another, and depend sensitively on the value of the rotational parameter K.

We studied models with two different rotational parameters. The first value was chosen to amount $K \sim 10^{-15}$s, which is supported by pulsars observations. For this K value, the heating due to thermal creep of pinned vortices and motion of proton vortices in the interior of the star yield considerable enhancements of the surface temperatures of middle aged pulsars with respect to the models which ignore heating. This leads to closer agreement with the observed data in the case of enhanced cooling, which is even more improved for the case of the fully accreted envelopes.

The observed upper temperature limit for PSR 0950+08 seems to rule out the strong pinning models, whereas the weaker pinning models are consistent with the observations (the pinning models differ by the value of the pinning energy in the inner crust). The other heating processes – from chemical heating to dissipative motion of neutron vortices in the crust to crust cracking – have no observable effect on the cooling. Our result for heating due to crust cracking is in contrast to the one obtained by Cheng et al., who find a large effect especially on the late cooling stages. The difference arises from different expressions adopted for the heating rates.

The four oldest pulsars of our sample rotate very fast with periods of a few milliseconds. Hence the rotational parameter for millisecond pulsars is smaller than that for the bulk fraction of the population by 7 orders of magnitude ($K = 10^{-22}s$). For this value only the late cooling stages are affected by heating. We find that the heating due to thermal creep of pinned vortices and chemical heating of the core has the largest impact on the surface temperatures of millisecond pulsars. Again, the strong pinning models leads to surface temperatures which are larger than one of the upper limits deduced for the millisecond pulsars.

As far as we know, the published cooling simulations of neutron stars which account for internal heating were performed in one spatial dimension. Such a treatment is only possible if the angle dependent heating rates are averaged over spherical shells. By comparing the outcome of one-dimensional simulations with fully two-dimensional simulations, based on a recently developed numerical code (Schaab & Weigel, 1998), we could confirm the validity of this procedure.

The knowledge of the input parameters for cooling simulations such as the composition, the superfluid gap energies, and the possible existence of an accreted envelope, etc. is far from being complete. The number of parameters involved in the cooling simulations increases when the internal heating processes are taken into account. In principal, one could expect to derive some of the parameters associated with these phenomena by means of comparing the theoretical cooling models with the body of observed data. This attempt needs to be supplemented with the analysis of terrestrial experiments, other astrophysical observations, as well as future theoretical studies. Nevertheless, the observed data already constrain the microphysical input, as, for instance, for the scenaria of heating via vortex creep.

Tables containing detailed references to the ingredients used in the simulations, the observational data, and the resulting cooling tracks can be found on the Web: http:/www.physik.uni-muenchen.de/sektion/suessmann/astro/cool.

Published in: Astron. & Astrophys. **346** (1999) 465