Exploring the Transient Sky: From Surveys to Simulations

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Summary

Transient sources are celestial objects that are not always visible in the sky, but alternate short periods of time when they are very bright (outburst) and much longer periods when they are not visible at all. In this thesis entitled "Exploring the Transient Sky: from Surveys to Simulations" we explore one of the most important parameters in the characterisation of these sources: their rate, i.e. how many of them go into outburst in a region of the sky, in an interval of time.

Even though many of these sources are known in optical and in X rays, only a few have been so far discovered at low radio frequencies (below 500 MHz). Observing at these low frequencies with good precision has not been possible until the last few years, when new technologies made it feasible to build new generation radio interferometers, like LOFAR. These new instruments do not use any big dishes, have no moving parts, and are pointed digitally (by applying different delays to different antennae according to the geometry of the instrument).

After performing observations, in order to find out if any transient was found, we produce images and feed them to a Transient Pipeline, which analyses them and gives out the results. One of the main components of this pipeline is the extraction of all the sources present in the images. This is performed using so-called source finder software. In Chapter 2 of this thesis we analysed the performance of the software that is currently in use, PySE. We have demonstrated that PySE is able to measure correctly the noise of the images and extract the sources at the right positions and with correct fluxes. We have also evaluated the best parameters that should be used in PySE when it is embedded within the LOFAR Transient Pipeline (TraP).

In Chapter 3 we have performed a survey of four fields with LOFAR, looking

for transient sources. Unfortunately, we did not find any transients, but we were able to set constraints on the transient rate. In order to do this we have considered two parameters of the transient events: the fluxes and the durations of the outbursts. The fact that we did not detect any transient implies that no outbursts brighter than the minimum flux that would have been visible in all of our observations happened. This approach was already known and used in the past and we have improved it as follows: considering the fact that it is the noisiest observation that regulates the minimum flux we can constrain, we have discarded it and re-calculated the limit on the transient rate with a dataset that does not include it anymore. This lets us have information on fainter sources because the noisiest image in the new dataset is more sensitive. We have then applied this in an iterative way, and it was possible to constrain the rate on outbursts up 3 times fainter than we could previously. In order to take into account the duration of the outbursts, we used the fact that two observations separated by a time interval equal to the duration of an outburst are most sensitive to it. This is because if they were closer, the outburst could be still ongoing in both, and would not be treated as transient, whereas if they were further apart the outburst could have happened in the gap between them and be missed. This way we could identify the observations we performed that were effectively sensitive to outburst of different durations: we reconstructed the effective survey for different durations of the outbursts, and using this new information we were able to calculate limits on the rate of outbursts as a function of their durations and found a strong dependence neglected in previous works. We have also compared the limits we can set on the transient rate to the ones that other surveys have set at different radio frequencies, with different telescopes. The main result of this comparison is that low frequency surveys are more sensitive to transients that emit coherently. These transients are peculiar for the way that they emit, and are predicted to be generated by exotic sources that remain among the main mysteries of modern radio astronomy.

In the former analysis about the transient rate, the flux and the duration of the transients were considered one at a time, never together, i.e., we calculated the transient rate for transients of different fluxes and then the transient rate for transients of different durations separately. Considering all the three quantities (flux and duration of the transients, and transient rate) at the same time is very important but also very complicated, and to do this we have decided to create simulations. These simulations were described in Chapter 4. For this project we have simulated surveys, like the one performed in Chapter 3. We have artificially generated millions of transient events starting an outburst at random time and with different fluxes and durations. These outburst will therefore be detected only if they are ongoing when an observation happens (this depends on their start time and duration), and if they are bright enough. We then checked if they were detected by the given survey that was tested. Different

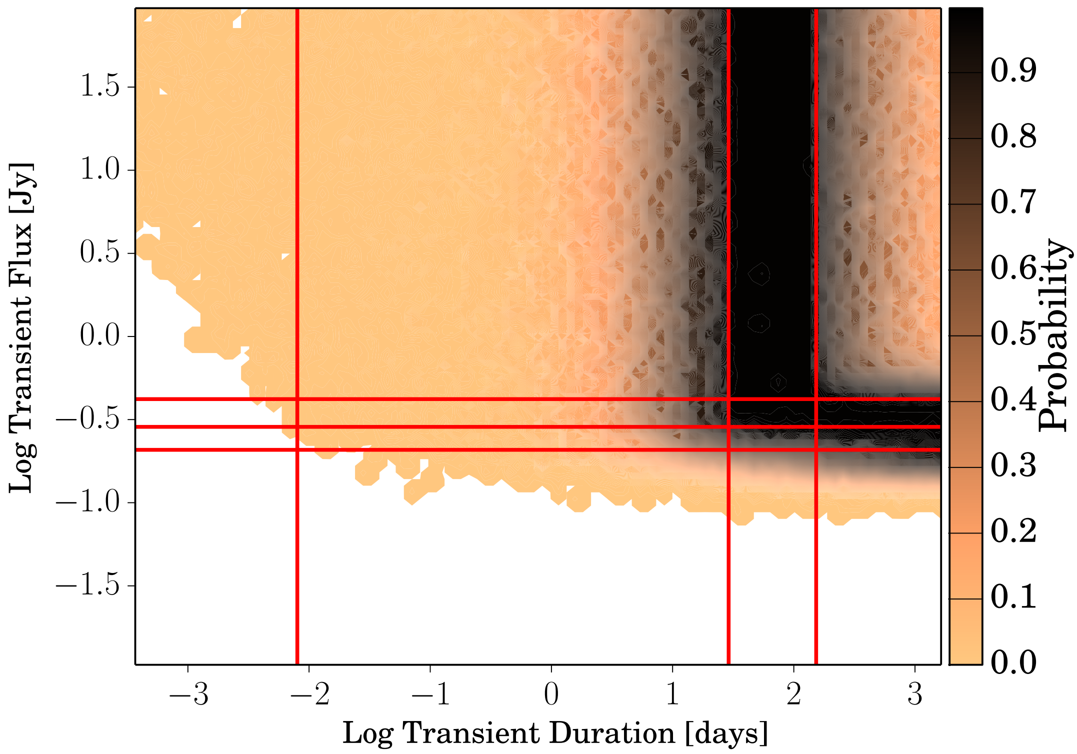

Figure A: Probability for transient detection as a function of flux and duration.

surveys would give different results. As mentioned, the probability of the transients to be detected will depend on their fluxes and durations, therefore we can evaluate for each combination of flux and duration the probability that a transient with those features would be detected by that survey. The probability is calculated as the ratio of the detected transients and the total number of transients with that particular combination of flux and duration. An example of an output map from this simulation is given in Figure A. Combining this with the actual results of the survey, we can finally convert the probability into a transient rate, meaning that we can now provide values, or limits, to the transient rate for every combination of flux and duration, evaluating both at the same time, as we planned to do.

The simulations we have developed depend neither on what these transient sources are, nor on the survey strategy that is used. In fact, in Chapter 5 we have then decided to use the same method for a different purpose: evaluate the duty cycle of Low Mass X-ray Binaries. These are celestial sources composed of two objects: a compact object (a neutron star or a black hole) and a normal star. The compact object is very massive (1.5 to 15 times more massive than the Sun) and extremely dense and, as a result, has a very powerful gravitational attraction. The normal star is less massive than the Sun and is extremely close to the compact object. The result is that the nor-

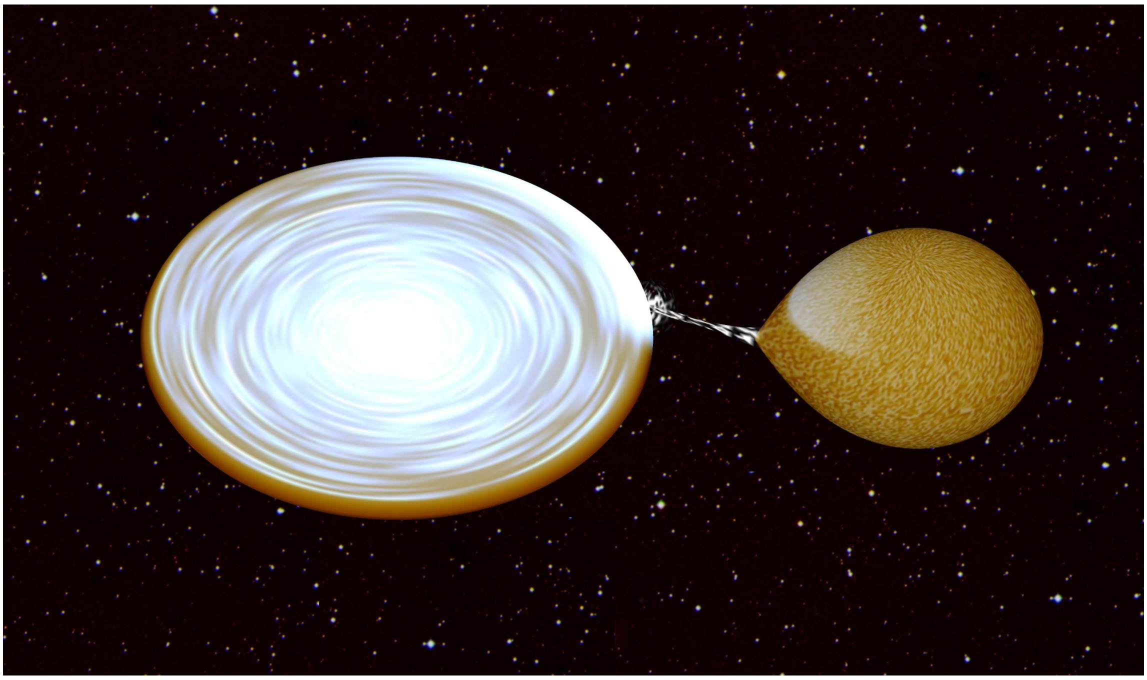

Figure B: Artistic impression of a Low Mass X-ray Binary system in outburst. The compact object is located at the centre of the disc on the left hand of the figure and is too small to be visible. The disc is very bright and is dominating the emission. The companion, a normal star is not spherical, but elongated towards the compact object due to its strong gravitational force.

mal star is orbiting the compact object and it is so close that the gravitational force of the compact object is able to strip material from the outer layers of the star. This phenomenon is known as accretion. This material forms a disc around the compact object and eventually reaches it. An artistic impression of this phenomenon can be found in Figure B.

When the disc is full, instabilities start and matter falls rapidly towards the compact object. At this time the source becomes very bright and an outburst starts. These sources are not permanently in outburst: after most of the disc gets depleted, they become much less luminous, and before a new outburst can start, a new full disc has to form. The ratio between the duration of an outburst and the time interval between two consecutive outbursts is known as the duty cycle. It is not easy to put constraints on this quantity because multiple outbursts from the same source should have been detected, moreover, undetected outbursts could affect the estimation of this parameter as well. Furthermore, they are not periodic, and the value of the duty cycle can vary up to a factor 2 for the same source; the duration of the outburst can vary as well. Another factor that can affect our measurements of the duty cycle is that it is possible that we do not detect an outburst from a source, but we do detect the next one. This way we can overestimate the time between outbursts and therefore underestimate the duty cycle.

In order to constrain the duty cycle of Low Mass X-ray Binaries better we have performed simulations. As done for Chapter 4, we have artificially created sources that undergo multiple outbursts, and for which we know the value of the duty cycle. For these outbursts we also know when they start and for how long they last. We then consider a survey dedicated to detecting these outbursts. Some of them will be detected, while some others will be missed, according to the start time and the duration of the outbursts. This way we obtain a catalogue of all the outbursts that were detected. Using this catalogue we can calculate the duty cycle we can infer for the sources we created. Comparing the calculated value to the input value of the duty cycle, we have an idea of how well the survey we used can estimate this parameter. We have also tested different survey strategies in order to understand which one is the best.