THE ASTROPHYSICS OF *ULTRA-COMPACT BINARIES*
A WHITE PAPER FOR THE ASTRO2010 DECADAL REVIEW

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Primary panel: SSE

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Definition

Ultra-compact binaries are objects which have orbital periods shorter than one hour. Both stars must be compact and are typically degenerate and hydrogen deficient. The class includes interacting AM CVn stars, ultra-compact X-ray binaries, detached double white dwarfs, double neutron stars, white dwarf/neutron star binaries and as yet unobserved binaries such as black holes with neutron star or white dwarf companions.

Scope

Ultra-compact binaries allow us to study unique (astro)physical phenomena specific to their ultra-short periods and the H-deficient nature of the components. This white paper focuses on:
1. Gaining insight in binary evolution by understanding the formation of these systems. 2. Understanding fundamental physics of gravitational wave emission and mass transfer via observation and theory. 3. The question of mass-transfer stability and the (often explosive) physics of compact object mergers. 4. Charting the ultra-compact binary population. 5. Testing accretion physics in H-deficient regimes.

Astrophysical context and Relevance

Stars are the building blocks of the Universe, and understanding the physics of their formation and evolution is foundational to making progress in many branches of astrophysics. Binary stars play a special role in this for several reasons. Interacting binaries allow us to probe stellar evolution processes that cannot be studied in single stars, such as literally exposing the internal structure of stars. They also give rise to energetic, accretion-driven phenomena, e.g. type Ia supernovae (SNIa), that can be used to identify and study stellar populations out to cosmological distances. Only in binary systems can stellar masses be measured accurately and progenitor masses inferred, constraining the major open question of the death of stars: which stars form white dwarfs (WD), neutron stars (NS), and black holes (BH), and how does this take place? Finally, the large fraction of stars in binary systems makes the study of binaries essential for understanding of the physics of stellar evolution.

Ultra-compact binaries are particularly relevant for the question of *the formation of compact binaries*, which requires the formation of compact stellar remnants as well as significant angular momentum loss via common-envelope stages. This process creates the vast majority of objects responsible for high-energy phenomena in the Universe. Ultra-compact binaries have often experienced two such episodes. They are also spectacular *probes of the extreme physics* at high energy and high density, being strong gravitational wave (GW) sources (the only guaranteed sources for LISA, Fig. 1). They harbor accreting millisecond pulsars and when merging they may explode as SNIa or short gamma-ray bursts (GRBs), leave low mass WDs or hydrogen-deficient giants.

Ultra-compact binaries are of general interest as laboratories for studying *the physics of accretion*, which produces the bulk of high-energy radiation in the Universe and is central to understanding such disparate phenomenon as SNIa explosions and the growth of super-massive BHs. Ultra-compact binaries are special since they combine the accretion of hydrogen deficient material (a feature unique to this population) with short time scales for the accretion processes. This offers the possibility of testing the physical theories in a substantially different environment.

Progress in studying ultra-compact populations is currently hampered by the small number of systems known. However, the next decade holds enormous promise for the study of ultra-compact binaries, due to the advent of large wide-field (and variability) surveys to find new systems, efficient optical and near-IR spectrographs combined with (extremely) large telescopes to allow detailed characterization of their properties, and the imminent advent of GW astronomy, which will allow studying these populations in unprecedented detail.

1. Gaining insight in binary evolution: How do ultra-compact binaries form?

An ultra-compact binary consists of compact stars, formed from the cores of well-evolved stars, and thus has much lower orbital energy and angular momentum than the progenitor binary that contained giants[1]. The binary is thought to shrink mainly during a phase of unstable mass transfer and ejection, the spiral-in. If the outcome of this process is derived by assuming that the change in orbital energy is enough to eject the giant's mantle, the predicted properties of the ultra-compact binary do not match the observations of double white dwarf binaries. These properties can be matched with the assumption that the giant's mantle is ejected carrying the specific orbital angular momentum[2], but this begs the question how the required energy is provided. It is clear that a more complete theoretical description is required that takes into account both energy and angular momentum. For neutron stars and black holes the existence and magnitude of asymmetric kicks imparted during the supernova event add to the uncertainty[3]. Of special interest is the formation of ultra-compact binaries in stellar clusters, both because many field systems must have originated in clusters and because ultra-compact systems are over abundant and seem to have different properties in dense clusters, implying that dynamical encounters play a role in their origin[4].

To proceed, we envisage a two-pronged approach using detailed studies of individual systems on one hand, and of the whole population on the other hand. Any viable evolution scheme must be able to reproduce the exact properties (such as component masses, orbital period, age, system velocity) of each observed system. Such scheme must also reproduce the distributions of and correlations between these properties in the population of ultra-compacts. Observationally this implies the accumulation of large homogeneous samples of ultra-compact binaries, and the detailed follow-up of a number of individual systems.

Prospects: Significant progress can be expected in the next decade, in particular from the combination of the large-scale (X-ray, UV, optical, NIR, radio and GW) surveys paired with population modeling to explore the full parameter space of possible binary evolution. When combined, the convolved uncertainties in binary evolution will be significantly constrained. Much more realistic physical models for star formation, supernovae and even common envelopes will be possible. Improved numerical modeling of dense stellar systems combined with deep observations of globular clusters will constrain dynamical formation processes.

2. Understanding physical interactions: evolution and mass transfer

Once formed as a detached ultra-compact binary, the system will evolve towards shorter orbital period via angular momentum loss until the components reach contact. The system merges (Sect. 3) or survives as an *interacting* binary, evolving to longer periods as a result of mass transfer, even though the orbital angular momentum still decreases. Known interacting systems are the double WDs or AM CVn systems and WD-NS systems (ultra-compact X-ray binaries, UCXBs). The UCXBs are strongly overproduced in globular clusters and may actually be the dominant population of X-ray binaries[7].

For the orbital shrinking phase, GW radiation and possibly angular momentum loss via magnetic stellar winds dominate, but tidal effects and interactions between magnetic components can alter the evolution[8]. Associated time scales in these ultra-compact binaries are short enough to measure period evolution on human time scales, in particular for eclipsing systems (as found recently[9]), systems harboring radio pulsars and when GW measurements become available (which can probe even $\ddot{P}_{\text{orbit}}$). This allows tests of GW predictions as well as magnetic interactions and gives a handle on the importance of tides in these ultra-dense objects.

In the expanding phase, mass transfer/loss and associated angular momentum loss complicate the orbital evolution. Still, time scales are short and the evolution can be followed in real time
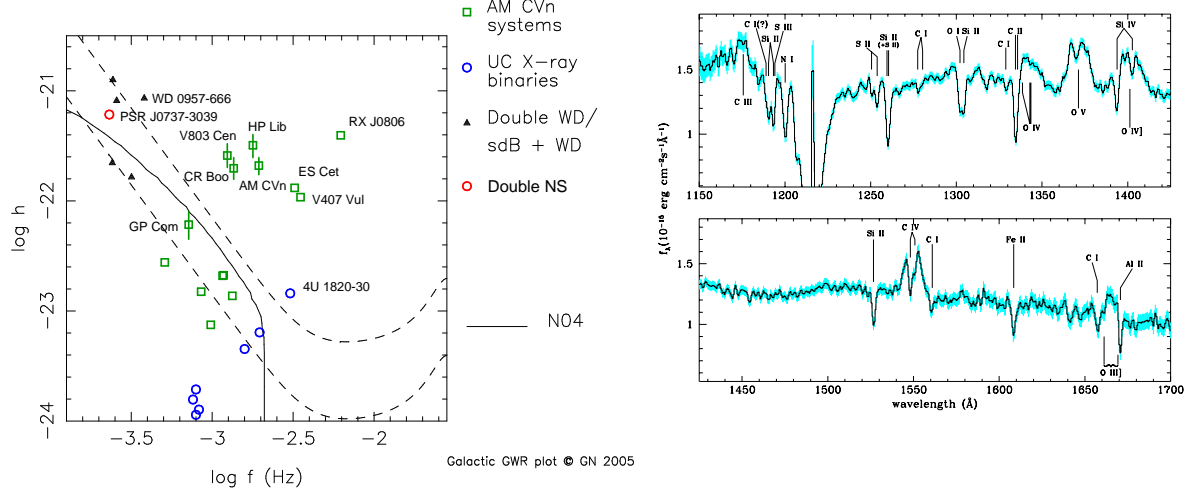
Figure 1: Left: known ultra-compact binaries as GW sources (frequency vs. strain) compared to the LISA sensitivity. Right: UV spectrum of the UCXB 4U 1626-67 [5]

by measuring period derivatives, while mass-transfer rates can be inferred from the (bolometric) luminosity and system parameters when (parallax) distances are known[10]. The mass-transfer rate is set by a combination of the GW losses and the internal structure of the donor stars, which thus can be inferred, although magnetic interaction and self-irradiation need to be taken into account. The donor stars have, so far, never been observed, but when irradiated they may be detectable in the IR. Abundance patterns in the transferred material can be determined from accretion disk spectra (Fig. 1) and often can be used to determine the progenitor system[11]. Due to the compact size of the systems, the disks hardly emit in the (near-)IR, allowing study of the unknown mechanism of jet launching from compact objects, in that wavelength range[12].

Prospects: With dedicated, short timescale variability surveys and piggy-back programs to find many new systems (Sect. 4), the prospects of using eclipsing systems for evolutionary studies are excellent. Direct measurement of the evolution of the shortest period interacting systems (via GW measurements or X-ray, UV, optical and radio monitoring of the newly discovered systems), combined with determination of current mass-transfer rates for the longer period systems, will provide stringent tests of the accepted GW driven evolution model. For this distance measurements are crucial (VLBI, GAIA). The results of detailed nucleosynthesis calculations combined with binary evolution scenarios can be compared with high quality (UV/optical/NIR) spectra to test the formation mechanisms.

3. WHEN IS MASS TRANSFER STABLE AND WHAT HAPPENS IN COMPACT OBJECT MERGERS?

A critical juncture in the life of an ultra-compact binary is the period just after mass transfer commences in the system, called contact (which occurs at orbital periods between 2 and 15 minutes for systems with at least one WD, and at millisecond periods for NS and BH systems). The system either merges, or – when at leat one WD is present – may survive to become an interacting binary.

To survive, the mass transfer must be stable, and this depends on several factors: the mass ratio, angular momentum loss mechanisms, and the internal structure of the donor[13]. Accretion in these systems can proceed directly onto the accretor[14], which destabilizes mass-transfer by sinking angular momentum into the accretor's spin. This so-called "direct impact" phase (Fig. 2) may very well be associated with two very-short period binaries found as ROSAT X-ray sources, HM Cnc and V407 Vul (the shortest period binaries known at 5.4 and 9.5 min resp.). Tidal coupling can return angular momentum to the orbit (but on very uncertain time scales[13]), heating

both components at the same time. This heating can influence the donor's response to mass loss and hence affect mass transfer stability. Even if mass transfer is stable, binary survival is not guaranteed. Mass transfer rates can become super-Eddington, and it is unclear what happens in these cases. Accretion-sparked thermonuclear explosions on the accretor may also destroy the binary during this phase shortly after first contact (Sect. 5). The properties of the surviving population depend critically on the interplay of these physical processes and can be used to constrain them.

When mass transfer is unstable, a catastrophic merger event cannot be avoided. The further evolution of the rapidly rotating merger product can produce several extremely interesting phenomena, including: collapse to a NS, formation of an R CrB star (helium-rich giant), or explosion as a SNIa. In the context of NS and BH binaries, mergers can lead to short GRBs. The resulting disruption of a NS in such merger events sheds light on the nuclear equation of state and physics at extreme density. While theoretical advances detailing the possible outcomes and the phenomenology of the mergers have been made in the last decade (with significant breakthroughs in the fully relativistic modeling of BH mergers[15]), basic questions remain: Can WD mergers explode as SNIa? If so, under what conditions? Do merging NSs and BHs produce GRBs?

Prospects: The wide field and variability surveys will find many new ultra-compact binaries and extra-galactic merger events. Wide-field spectroscopic studies can be used for confirmation of candidates. Larger samples will enable us to determine relative numbers of shrinking and expanding systems and thus to directly determine the survival and merger fractions. A combination of increased numbers of observed SNIa and GRBs and better statistics on their occurrence in different environments will provide the observational handle on the question whether they are (sometimes) related to mergers. This should be complemented by further theoretical modeling of the merger processes and the early contact phase of WD ultra-compact binaries. The surviving binaries must be studied in detail to determine the distribution of their properties, which constrain the physics influencing survival. Finally, GW studies of the NS and BH mergers with high-frequency detectors such as LIGO and VIRGO, and the observations of WD mergers and pre and post-contact WD systems with LISA will provide unprecedented detail (LIGO) and statistics (LISA).

4. CHARTING THE ULTRA-COMPACT BINARY POPULATION

Many of the issues discussed earlier have a strong influence on the number of ultra-compact binaries that exist in our Galaxy. Conversely, determining the absolute and relative number of 'flavors' of ultra-compact binaries provide direct tests of the physics of their formation, evolution, mass-transfer stability and merging.

Current predictions based on population modeling (Sect. 1), combined with calibration from the observed systems[16], estimate the Galactic numbers at around 10^8 for double WDs, several 10^6 each for double NS-NS and NS-WD systems. A large population of ultra-compact binaries with NS and/or BH with periods below 1 hr may form, strongly influencing merger rates[17]. The predicted numbers of AM CVn systems and UCXBs are very uncertain at around 10^6 for each case[18]. Most of the studies up to now have concentrated on particular populations, but the relative numbers are easier to determine and will give insight in the relative importance of different formation channels. The rates at which the systems get into contact is of particular interest, as this may lead to (explosive) mergers or to the formation of interacting binaries (Sect. 3). A combination of finding more systems before and after they merge (for which recognizing the merger product(s) is a pre-requisite) has a great potential for constraining merger rates.

Prospects: The next decade promises to be a golden age for the discovery of new systems, in particular large samples with homogeneous selection effects due to the advent of large-scale, wide-field surveys. GW discoveries with LISA, will identify the spectral shape of the unresolved fore-
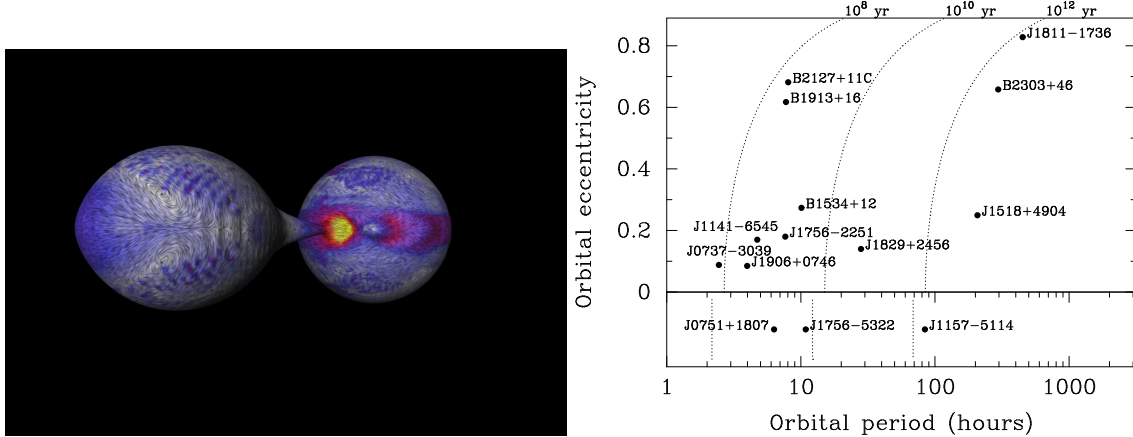
Figure 2: Left: Snapshot of a simulation of direct impact accretion (Motl, priv. comm). Right: period – eccentricity of the known NS binaries with their merger time indicated[27].

ground and more than 10,000 individual systems (complete for periods shorter than ∼12 min!). These samples will shed light on binary evolution models and the star formation history of the Galaxy. Distance measurements, in particular by GAIA and LISA (for several thousand), give the necessary third dimension to determine space densities Galactic structure. The (planned) increase in the scale of the variability surveys (e.g. Palomar Transient Factory, Pan-Starrs, LSST) will open up the possibility of directly observing even very rare events such as mergers and common-envelope phases. For the brighter sources and events, extra-galactic studies will become an important new strand of investigation, largely removing the problems associated with the uncertain distances for the Galactic populations.

5. TESTING THE PHYSICS OF ACCRETION IN H DEFICIENT SITUATIONS

Because in interacting ultra-compact binaries the transferred matter is H deficient (typically He or C/O rich, e.g. Fig. 1), accretion disk theories developed for H-rich gas can be tested in different environments. For instance, the disk-instability model applied to He disks suggests the possibility of steady cool (i.e. neutral) disks[19], which indeed seem to be observed in the long-period AM CVn systems, while applied to UCXBs the disk-instability model seems to fail to explain some persistent systems[20]. The observed He and C/O disk spectra are very different from their H-rich counterparts. For instance the He-rich disks in AM CVn stars show a mysterious "central spike," a third emission peak (in addition to the omnipresent double peaks from the disk) that seems to originate from the accretor, which has never been observed in H-rich systems. There is considerable progress in the (spectral) theoretical models for H-deficient accretion disks, but they are not yet accurate enough for quantitative comparison with the observations[21].

The H-deficient material ends up on the accreting WD or NS. Accumulating H-rich material on WDs leads to expansion to giant dimensions, steady H burning or shell flashes (novae), depending on the specific accretion rate and the local gravity. For He accretion the overall scheme is similar, although much work is still needed to determine the exact picture. The big difference is that for the He ignition much higher pressure and densities are needed, leading to much more violent and rare He novae, as compared to H novae. At the relatively low accretion rates reached in AM CVn systems the ignitions may be so violent that they lead to thermonuclear explosions, somewhat like small scale SNIa (termed .Ia supernovae[22]). He accretion may also alleviate some of the problems that may prevent H accreting WDs from reaching the Chandrasekhar mass and exploding as full-blown SNIa[23]. To date no C/O accreting WDs have been observed and their fate has not been studied in detail.

Accretion onto a NS often leads to thermonuclear explosions that are observed as type I X-ray bursts. The situation is slightly different from WD accretors, as often in H-rich accretion the H is first (in part) stably burnt into He, which then ignites unstably, or even both H and He burn stably into a C layer that then explodes in a so-called super burst[24]. The difference between H-rich and He- or C/O-rich accretion then becomes more subtle, as the He-bursts from steadily burnt H are different from the He bursts from He accretion, only due to the lower temperature in the accumulated He layer in the latter case. Although from optical, UV and X-ray spectra there is evidence for accretion disks that are C/O dominated and thus He deficient, no C/O bursts have been observed. In contrast, for some sources that seem to have C/O disks, bursts have been observed that are best explained as He bursts[25]! Apart from obvious solutions such as misinterpretation of either burst or disk spectra, one possibility would be the spallation of C/O nuclei into He nuclei, a spectacular nuclear physics experiment.

Prospects: With the expected significant enlargement of the number of known systems, the prospects are excellent for obtaining spectra of many H-deficient accretion disks, to probe composition, structure, winds and jets, over a large range of parameters. Progress in theoretical understanding of accretion disk spectra can be anticipated because of recent developments in (magneto)hydro-dynamics calculations[26]. A systematic study of accretion disks and their stability for different chemical compositions – different molecular weights, ionization temperatures, opacities and viscosities – may become an important ingredient for answering the now 30-year-old question of the structure and stability of accretion disks.

The many newly discovered systems will allow systematic study of disk instability outbursts and the (thermonuclear) explosions on WDs and NSs. Combining the novae/burst observations with the chemical composition information coming from the disk spectra will allow an unprecedented detailed test of our understanding of accretion and ignition physics, and thus provide a solid basis for understanding in which circumstances accretion onto WDs may push them over the Chandrasekhar limit, so that they explode as SNIa.

Necessary Facilities

- *Wide-field and variability surveys* For optical work many projects are under way or planned, (e.g. SDSS, PTF, Pan-Starrs, SkyMapper, ESO VST, Vista, LSST). Limited sampling in the UV is done by GALEX, XMM-Newton, Swift, TAUVEX so new missions are needed (e.g. the Russian WSO-UV; HORUS and later MUST, ATLAST). Small-scale X-ray surveys are being undertaken using Chandra and XMM-Newton so new missions are needed (many are proposed, of which the eRosita instrument is most advanced). Radio surveys are needed to find new pulsars. GW measurements with LISA will discover thousands of new systems and LISA and LIGO will provide unique information on the mergers and their rates.

- *X-ray/UV/Opcital/NIR spectrographs* Wide-field/multi-object spectroscopic instruments (such as WFMOS) are needed for confirmation/follow-up of candidates. For detailed (kinematics, abundance) studies, X-ray, UV, optical and NIR spectrographs with sufficient resolution (R several thousand) and throughput (e.g. X-Shooter), mounted on large to very large telescopes, are needed (with magnitudes of 21-22 even 8-m-class telescopes are often too small, in particular when phase resolved spectroscopy is needed). High-speed (photon counting) detectors are needed to cover the shortest time scales. For calibration of luminosities, parallax measurements with GAIA or VLBI are crucial.

- *Monitoring and high-speed instruments* All-sky X-ray monitors are important for finding variable objects. Eclipsing systems, found by GAIA, LSST and LISA must be monitored with optical, UV, X-ray and radio instruments to follow the long(er) term evolution. For that it is

important to keep high-speed instruments on modest-sized facilities (such as an international network of dedicated (small) telescopes, e.g Las Cumbres Observatory and SONG) and to keep high time resolution in future UV missions. GWs as measured by LISA will directly follow the evolution of thousands of the shortest period systems. Monitoring of radio pulsars in binaries will reveal the evolution of NS systems.

- *Theoretical and numerical tools* Detailed theoretical modeling of the evolution of binaries, the onset of mass transfer and the merger process itself relies on further developing (relativistic) numerical methods (combining hydrodynamics with radiation and magnetic interaction) and continued developments of computer power. Significant further efforts in theoretical spectral modeling of accretion disks, which requires understanding of their physical structure are needed.

CONCLUSION

We conclude that a large number of ultra-compact binaries, studied in great detail, will allow us to study a number of (astro)physical phenomena that are of general importance in our understanding of the Universe, in particular the formation of all compact binaries, many high-energy phenomena such as SNIa and GRBs, and our general understanding of accretion. In the next decade this possibility will become reality as there is enormous promise for finding new systems, in particular with optical wide-field and variability surveys and even more with LISA.

These large numbers will enable statistical studies that constrain binary evolution, but also fundamental physics of interaction and merger. This can only be done if Galactic studies of the faint and common systems are combined with studies of the rare (but explosive) phenomena far away.

Recommendations Crucial facilities are

- GW detectors (LISA, LIGO) for finding and following systems up to merger.
- Wide field and variability surveys (PTF, Pan-Starrs, SkyMapper, VST, Vista, LSST) to find (rare) systems and phenomena.
- X-ray instruments (timing and spectra, as proposed by many notices of interest).
- New large UV spectrograph in space (e.g. WSO-UV, HORUS, MUST, ATLAST). The lack of missions on the horizon is worrying.
- Optical (multi-object) spectrographs with R = 5,000-10,000 on (extremely) large telescopes (WFMOS, X-Shooter).
- Radio surveys for detecting pulsar binaries and following their evolution.
- Network of small(er) (X-ray/UV/optical), rapid-responde telescopes obtaining light-curves on short (second to hour) as well as long (days to weeks) time scales.
- Sufficient opportunities for obtaining grants for theoretical/numerical developments.

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