The First High-Contrast Images of Near X-Ray Binaries

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Overview

As part of a pilot study aiming to explore the immediate environments of X-ray binaries, we obtained NIRC2 observations taken with Keck of a dozen X-ray binaries from 2017 to 2020. These consist of the first high-contrast adaptive optics images of X-ray binaries, enabling us to probe a variety of phenomena from protoplanetary discs, to debris discs and fallback discs, as well as orbiting companions.

X-Ray Binaries

- X-ray binaries are composed of a **compact stellar remnant** (white dwarf, neutron star or black hole) accreting material from a **donor star**, and their interaction releases strong **X-ray radiation** (e.g. Tauris & van den Heuvel 2006).
- Historically, X-ray binaries have been divided into two distinct categories:
  1. **High-mass X-ray binaries (HMXB)** which harbour a massive O-B spectral type donor star that transfers mass onto the compact object via strong stellar winds (e.g. Mukherjee et al. 2006).
  2. **Low-mass X-ray binaries (LMXB)** which harbour a K-M spectral type star that overflows the Roche Lobe of the compact object, giving rise to strong accretion (e.g. Charles & Coe 2006).
- X-ray binaries are unique laboratories for studying a variety of astronomical phenomena under extreme conditions.

Sub-Stellar Companions

- The first exoplanets were discovered around pulsars in the 90s (e.g. Wolszczan & Frail 1992), which means that sub-stellar companions can exist in extreme environments.
- Studies indicate that planets and brown dwarfs can exist in a variety of environments: from the hot Jupiters that orbit exceedingly close to their host star (e.g. Seager & Sasselov 1998) to those found excessively far – up to several thousands of AU (e.g. Naud et al. 2014).
- Recently, it was argued that X-ray binaries could host planetary systems (Imara & Di Stefano, 2018), detectable via transit spectroscopy.
- However, those systems are more likely to harbour wide orbit planets because of planet-star/planet-planet interactions that would push away the companions (e.g. Bonavita et al. 2016).

⟹ **We thus decided to explore the environment of X-ray binaries via direct imaging.**

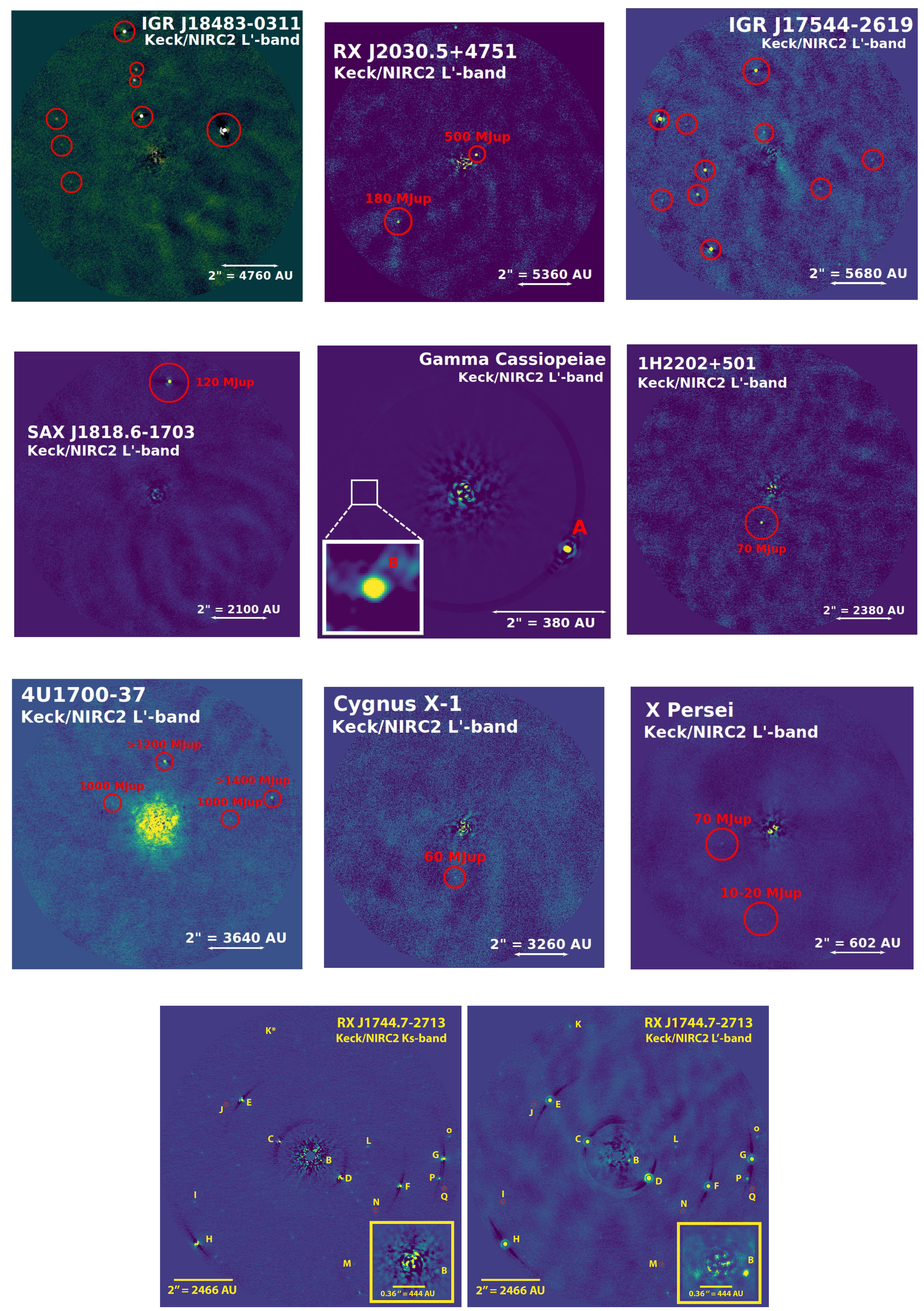
Observations

From 2017 to 2020, we observed a total of 14 X-ray binaries with Keck/NIRC2 and its vortex coronagraph (Mawet et al., 2005). Those X-ray binaries are near (< 2-3 kpc) to allow to probe ∼100-1000 AU scales environments and to have the sensitivity for detecting sub-stellar companions via direct imaging. The following table presents a summary of the observations.

UT Date	Target	Filter
2017 Sept. 8	RX J1744.7−2713, Cygnus X-1, γ Cassiopeiae, X Persei	L'
2018 Jan. 3	X Persei, 1H0556+286, RX J0648+4419, Vela X-1	L'
2020 July 11	RX J1744.7−2713, IGR J18483−0311, γ Cassiopeiae	L'
2020 July 12	RX J1744.7−2713	K_s
2020 July 12	SAX J1818.6−1703, 1H2202+501, 4U2206+543	L'
2020 July 13	4U1700−37, IGR J17544−2619, RX J2030.5+4751, 4U2206+543	L'

High-Contrast Images

The following figures present the first high-contrast images of the X-ray binaires from our sample in which we detected at least 1 source with a signal-to-noise ratio (SNR) > 5. Note that the estimated masses already calculated are indicated.



How can we determine if the sources are (sub-)stellar companions?

A detected source is not always necessarily bound to the system: it could be, for example, a bright background star. Some of the most common techniques to determine the nature of the sources are listed below.

1. **Astrometry (follow-up observations)**. It is the most rigorous way to confirm that candidates are sub-stellar companions to the host system. By taking additional data several days/months/years apart, we can study the proper motion of the objects and therefore conclude if they are bound or not.

   ⟹ Except for gamma Cassiopeiae, this kind of analysis will be available only in 3 to 10 years.

2. **Color-magnitude diagram**. If observations in two different bands are available, we can construct a color-magnitude diagram to determine if their color and magnitude are more coherent with stars or exoplanets.

   ⟹ We can construct this diagram only for RX J1744.7−2713, since we obtained data from both L'-band and Ks-band (more detail in J. Hlavacek-Larrondo's talk).

3. **Background probability**. Using 3D models of the sky (e.g. TRILEGAL, Girardi et al. 2005), we can estimate the expected number of sources in a certain area. Depending on the number of sources, we can calculate the probability of finding a source with the same magnitude of a detected candidate.

   ⟹ According to TRILEGAL, the expected number of sources is lower than the number of sources detected with a SNR > 5, for most of our sources. For example, TRILEGAL predicts ∼0.14 source for the field of view of IGR J17544−2619, however we detect 10 sources.

4. **More observations**. In order to study an object more in depth, we can ask for additional observations, e.g. spectroscopic analysis, other bands, etc.

Summary

- As part of a pilot study, we took the first high-contrast images of X-ray binaries, which makes the project new and exploratory.
- We detected a lot of candidate sub-stellar companions in many X-ray binaries, which suggests that they could exist and survive in those extreme environments.
- Future work: we will conduct a statistical study for the presence of sub-stellar companions (occurrence rate) in near (< 2-3 kpc) X-ray binaries, similarly to Baron et al. (2019).

References

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