THE FORMATION OF MASSIVE MULTIPLES

COLLABORATORS: JOHN TOBIN (+VANDAM TEAM), MAXWELL MOE (U OF A), STELLA OFFNER (U MASS)
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KAITLIN KRATTER (UNIV. OF ARIZONA)
WHERE DO WE BEGIN

- Stars, especially massive ones, are rarely alone
- Understanding star formation means understanding the frequency of multiples AND variations in properties as a function of mass
WHERE DO WE GO

- Stars, especially massive ones, are rarely alone
- Understanding star formation means understanding the frequency of multiples AND variations in properties as a function of mass
FORMATION: SAME OLD STORY

Kratter 2011

• Two dominant modes of binary formation:

• Filament / Core Fragmentation (Bate et al 2003, Fisher 2004, Offner et al 2010)

• Disk Fragmentation (better at high masses…) (Bonnell and Bate 1994, Adams et al 1989, Kratter et al 2008, 2010)

1000-10,000AU

10-100AU
Theories have not changed much*, but observations have

- ALMA and the VLA are revolutionizing the observations
- Reaching a critical mass of field star statistics as well

*updated RHD, MHD, non-ideal MHD, photoionization, chemistry, stellar + disk winds...
THEORY, MEET DATA

CORE FRAGMENTATION HAPPENS

JVLA OBSERVATIONS OF A GRAVITATIONALLY BOUND, YOUNG QUADRUPLICATE IN PERSEUS

Pineda, Offner et al, Nature 2015
DISK FRAGMENTATION HAPPENS…?!?
Theory, meet data

Tobin, Kratter, et al in prep

~200 AU

Fig. 1.—Two examples of single, binary, and multiple systems. The resolution across each panel is 328x328 grid cells. The single runs $\varpi = 2.9$, $= 0.018$ (top), $\varpi = 1.6$, $= 0.009$ (bottom). The binaries are $\varpi = 4.2$, $= 0.014$ (top), $\varpi = 2.4$, $= 0.008$, (bottom). The multiples are $\varpi = 3.0$, $= 0.016$ (top), $\varpi = 2.4$, $= 0.01$ (bottom). Black circles with plus signs indicate the locations of sink particles. These correspond to runs 5, 1, 9, 16, 7, and 4 respectively.

Parameterization, in which steady accretion occurs at a rate

\[ \dot{M}_d(r) = 3^{\frac{2}{3}} (r) = \frac{Q(r) c_s(r)}{3G}\] Using the definition of $\varpi$, $\varpi$ when the GI is active, the effective value of $\varpi$ induced by a strong GI is directly proportional to $\varpi$.

The magnitude of $\varpi$ has important implications for disk evolution. As discussed previously by KMK08, called $<\mu>$ in there) $\varpi$ affects $\mu$ through the relation

\[ \dot{\mu} = k_{\mu} , \mu = \frac{1}{\varpi} \] In our simulations $\dot{\mu} < 0$ so we expect $\mu$ to saturate at the value for which the two terms on the right of equation (27) are equal, $\mu = \frac{1}{\varpi}$.

The disk mass fraction $\mu$ increases with $B$, so both $Q$ and $\varpi$ have a positive effect on $\mu$, whereas $\varpi$ tends to suppress the disk mass. Note that, when $B$ is small and $\mu < 2B$, equation (23) implies $Q_d = \frac{3\varpi}{2\varpi}$ in accordance with equation (25). Because the effective value of $\varpi$ induced by the GI is a function of disk parameters, we cannot say more without invoking a model for $\varpi$ or $Q, \mu$ as in KMK08.

The scalings of disk properties with the dimensionless parameters of the problem are in accord with intuitive expectations. An increase in $\varpi$ corresponds to an increase in accretion rate at fixed disk sound speed, and as a result the equilibrium disk mass rises. An increase in $\varpi$ corresponds to an increase in the mean angular momentum of the infall at fixed sound speed, leading to larger disks that must transport more angular momentum, and thus again become more massive. An increase in $\varpi$ corresponds to an increase in the rate at which the disk can transport angular momentum and mass at a fixed rate of mass and angular momentum inflow, allowing the disk to drain and reducing its relative mass. We use the above
DATA, MEET THEORY

IS THIS REALLY A FRAGMENTING DISK?

\[ \begin{align*}
M_{*s} & \approx 1M_\odot \\
M_d & \approx 0.3M_\odot \\
M_{cl} & \approx 0.08M_\odot 
\end{align*} \]

Tobin+in prep, Kratter & Lodato, ARAA 2016
THEORETICAL CELEBRATION!
NEXT STEPS: PROGRESS WILL NECESSITATE NUANCED COMPARISON WITH OBSERVATIONAL STATISTICS

• Can we go beyond multiplicity fraction?
• What do the distributions look like during formation?
• What do they like look in the field?
### Table 1

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### Revealed many new Class 0-II binary sources
YOUNG SOURCES REVEAL BIMODAL DISTRIBUTION

- Are we seeing two modes of binary formation?
- No observational selection against middle range, though possible that largest sources may not be bound

Tobin+2016a
Companions to massive stars have been detected through a variety of methods, including spectroscopy of the binary population. The initial conditions of MS binaries are also utilized as input parameters in binary population synthesis. We compare the approximate orbital period (P) and mass ratio (q) of binary systems with different observational techniques (regions enclosed with solid and dashed lines) used to identify companions to early-type stars at intermediate orbital periods (Fig. 1). We summarize our main results in MOE & DISTEFANO, IN PREP 2016. Finally, we emphasize that only recent observations of eclipsing binaries (Moe & Di Stefano 2015a, b, red), companions identified via long-baseline interferometry (Rizzuto et al. 2013, Sana et al. 2014, magenta), and binaries with intermediate-mass Cepheid primaries (Remage Evans et al. 2002; Belczynski et al. 2008) show only observational techniques where the orbital period is sensitive to companions across a certain interval of orbital periods. We detect early-type binaries. We analyze spectroscopic advances in the observational instruments and methods, especially interesting because low-mass X-ray binaries, millisecond pulsars, and Type Ia supernovae are expected to derive from early-type galaxies (Whelan & Iben 1973; Ruiter et al. 2011) and their properties of certain channels of binary evolution are highly dependent on the adopted MS binary statistics and the intrinsic binary statistics. To extend the baseline of the properties of low-mass companions (around early-type stars at intermediate orbital periods, see Fig. 1). Despite significant advances in the observational instruments and methods, q ≲ 0.4) can be estimated, and the nature of evolution can be inferred to recover the possible progenitors of Low-mass X-ray Binaries, Millisecond Pulsars, & Type Ia Supernovae.

Separately adjusting the input MS binary distributions significantly correlated with each other (Abt et al. 1990). Such as the period and mass-ratio distributions, may be highly dependent on the adopted MS binary statistics and other input parameters in binary population synthesis (Hurley et al. 2013, 2015, green) come close to probing this portion of the parameter space. Through a variety of methods, including spectroscopy, the initial conditions of MS binaries are also utilized as input parameters in binary population synthesis. We compare the approximate orbital period (P) and mass ratio (q) of binary systems with different observational techniques (regions enclosed with solid and dashed lines) used to identify companions to early-type stars at intermediate orbital periods (Fig. 1). We summarize our main results in MOE & DISTEFANO, IN PREP 2016. Finally, we emphasize that only recent observations of eclipsing binaries (Moe & Di Stefano 2015a, b, red), companions identified via long-baseline interferometry (Rizzuto et al. 2013, Sana et al. 2014, magenta), and binaries with intermediate-mass Cepheid primaries (Remage Evans et al. 2002; Belczynski et al. 2008) show only observational techniques where the orbital period is sensitive to companions across a certain interval of orbital periods. We detect early-type binaries. We analyze spectroscopic advances in the observational instruments and methods, especially interesting because low-mass X-ray binaries, millisecond pulsars, and Type Ia supernovae are expected to derive from early-type galaxies (Whelan & Iben 1973; Ruiter et al. 2011) and their properties of certain channels of binary evolution are highly dependent on the adopted MS binary statistics and the intrinsic binary statistics. To extend the baseline of the properties of low-mass companions (around early-type stars at intermediate orbital periods, see Fig. 1). Despite significant advances in the observational instruments and methods, q ≲ 0.4) can be estimated, and the nature of evolution can be inferred to recover the possible progenitors of Low-mass X-ray Binaries, Millisecond Pulsars, & Type Ia Supernovae.

In addition, we investigate all portions of the binary parameter space, including the properties of low-mass X-ray binaries, millisecond pulsars, and Type Ia supernovae that explode in elliptical (Kalogera & Webbink 1998; Kiel & Hurley 2006) and common-proper motion (Abt et al. 1990), etc. Each observational technique is sensitive to companions across a certain interval of orbital periods. We detect early-type binaries. We analyze spectroscopic advances in the observational instruments and methods, especially interesting because low-mass X-ray binaries, millisecond pulsars, and Type Ia supernovae are expected to derive from early-type galaxies (Whelan & Iben 1973; Ruiter et al. 2011) and their properties of certain channels of binary evolution are highly dependent on the adopted MS binary statistics and the intrinsic binary statistics. To extend the baseline of the properties of low-mass companions (around early-type stars at intermediate orbital periods, see Fig. 1). Despite significant advances in the observational instruments and methods, q ≲ 0.4) can be estimated, and the nature of evolution can be inferred to recover the possible progenitors of Low-mass X-ray Binaries, Millisecond Pulsars, & Type Ia Supernovae.
Identified 22 pre-MS+MS EBs with reflection effects in LMC:

- $M_1 = 7$-$16 \, M_\odot$, $M_2 = 0.8$-$2.4 \, M_\odot$ ($q = 0.06$ - $0.36$), and $\tau = 0.6$-$8$ Myr.

- $P = 3$ - $8$ days
- $R_1 = 4$ - $5 \, R_\odot$
- $R_2 = 2$ - $4 \, R_\odot$
- $T_1 = 20,000$ - $30,000$ K
- $T_2 = 4,000$ - $7,000$ K
There are still uncertainties in the evaluation of the fit at low masses ($\log M = 3.5, 2.0$) for solar-type primaries, we find: $\gamma = 0.1 - 0.3$. We display all our measurements after correcting for incompleteness and selection effects. Qualitatively, for all primary masses, we display the excess fraction ($q > 0.95$) for solar-type ($M_1 = 0.8 - 1.2 M_\odot$), A/Late-B ($M_1 = 2 - 5 M_\odot$), mid-B ($M_1 = 5 - 9 M_\odot$), early-B ($M_1 = 9 - 16 M_\odot$), and O-type ($M_1 > 16 M_\odot$). In the middle panel of Fig. 31, we display the power-law component of the mass-ratio distribution across large mass-ratios ($0 < q < 0.5$). At longer orbital periods, the slope is $\gamma = -3(\log P)$ for $P < 5$ days. At $P > 5$ days, the slope decreases, but the break in the mass-ratio distribution at $P \approx 5$ days provides a uniform mass-ratio distribution, while for $P > 5$ days, the mass-ratio distribution is rather complex. These variations in the mass-ratio distribution provide important clues towards steeper slopes.

The excess twinning fraction as a function of primary mass is shown in the top panel of Fig. 31 for solar-type, A/late-B, mid-B, early-B, and O-type stars. We group the data into five primary mass / spectral type intervals: solar-type ($M_1 = 0.8 - 1.2 M_\odot$), A/late-B ($M_1 = 2 - 5 M_\odot$), mid-B ($M_1 = 5 - 9 M_\odot$), early-B ($M_1 = 9 - 16 M_\odot$), and O-type ($M_1 > 16 M_\odot$).
PERIOD VS MULTIPLICITY FOR DIFFERENT PRIMARY MASSES

MORE BIMODALITY: SMALLER SCALES

Based on the above considerations, we can now fit the companion frequencies according to the analytic functions that fit the data. For early-type primaries, the companion frequencies are completely described by the functions:

\[ f(P) = \log P + \alpha \]

where \( \alpha \approx 0.08 \) near \( \log P \approx 0.02 \) and \( \alpha \approx 0.36 \) for \( \log P > 0.02 \). For late-type primaries, the companion frequencies are also fitting according to the same analytic functions, with \( \alpha \approx 0.07 \) near \( \log P = 2 \) and \( \alpha \approx 0.37 \) for \( \log P > 2 \).

Fig. 33.—

For all bins of \( q \), the large \( q \) and intermediate \( q \) bins are indicated for each primary mass bin. The primary mass bins are as follows:

- Solar-type: \( (M_1 = 0.8-1.2 \, M_\odot) \)
- A/Late-B: \( (M_1 = 2-5 \, M_\odot) \)
- Mid-B: \( (M_1 = 5-9 \, M_\odot) \)
- Early-B: \( (M_1 = 9-16 \, M_\odot) \)
- O-type: \( (M_1 > 16 \, M_\odot) \)

The data is grouped into the same five primary mass bins, and the frequency distribution parameters are used to adjust the fit.
MULTIPLICITY AS A FUNCTION OF MASS, NOT PRIMARY MASS
AN UPDATED LOOK AT MULTIPLICITY

MOE, KRATTER + IN PREP
A post-dictive theory of binary formation is now possible with remarkable data.

This will be crucial for understanding stellar evolution — if we can produce the observed sample, perhaps we can predict the more extreme, undetectable systems.