TWO-DIMENSIONAL STELLAR EVOLUTION

with 2DStars:

Introduction & Applications

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Binary Stars in Cambridge
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Two-dimensional Stellar Evolution:

2DStars

- science goal
- applications
- input physics
- decisions

Science goal

The goal is to develop a **general-use 2D, adaptable to 3D, stellar evolution code** (Izzard 2015) to model a variety of multi-dimensional phenomena in the evolution of single and binary stars.

- **Rotating Stars**
    - **Close Binaries**
        - **Star Formation**
            - **X-ray Binaries**

Vega

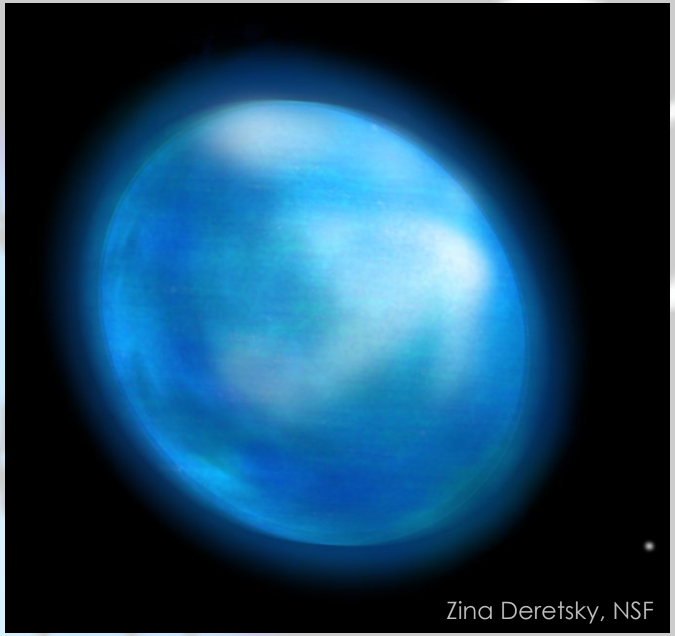
Altair

Applications (i)

Rotating stars

A large fraction of stars rotate rapidly, are not spherical and exhibit surface temperature variations.

- The centrifugal force caused by rotation changes the hydrostatic balance, which alters the structure. This affects intrinsic stellar properties like luminosity (Potter + 2012), oscillation frequencies (Reese 2015) ..
- Rotation distorts the shape of the photosphere.
- Rotation introduces a brightness asymmetry due to the variation in the flux flowing through the surface as a function of latitude (**von Zeipel's theorem**: higher radiative flux at higher latitudes).



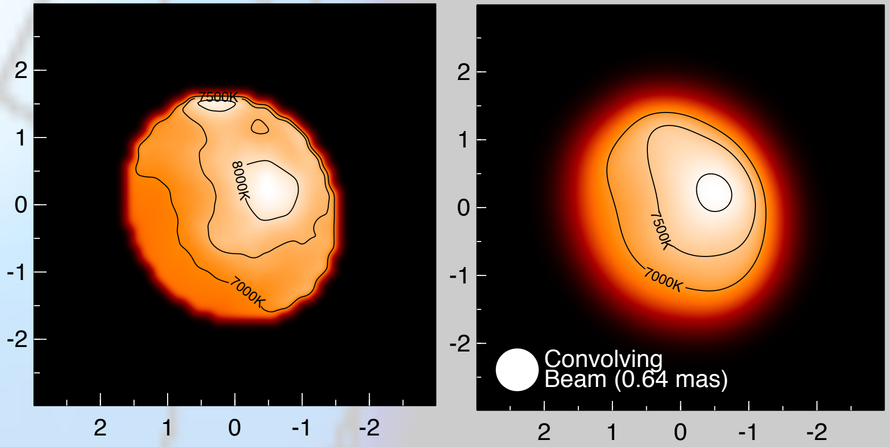


Image of **Altair** from **CHARA** interferometric array *(Monnier et al. Science, 2007).*

Altair rotates at 90% of its breakup velocity with a period of 9 hours (2.8 rev/day). This causes **the equator to bulge and darken (cooler).** $I_{eq} = 60\% \, I_{pole}$.

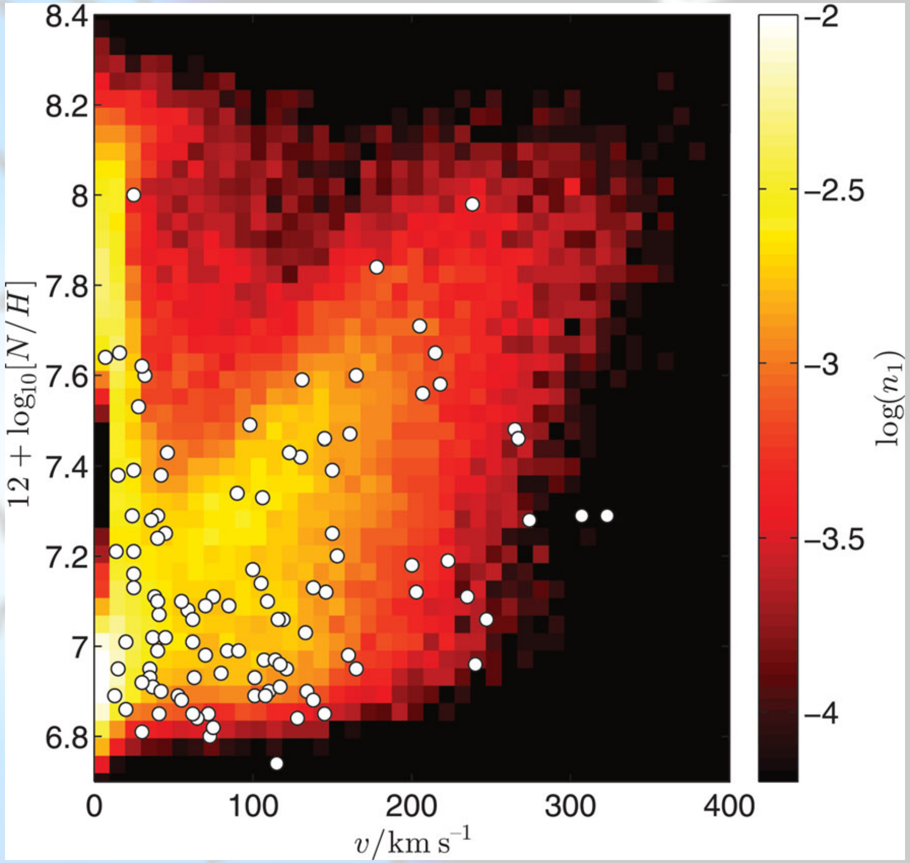
Applications (i) – cont'd.

Rotation:

- It alters the stellar chemistry by developing internal currents (such as the meridional Eddington-Sweet circulation)
- It couples to magnetic fields, commonly referred to as an $\alpha - \Omega$ dynamo (Schmalz & Stix 1991, Potter, Chitre & Tout 2012).
- It may affect mass-loss or cause wind anisotropies: g_{eff} effect/ κ_{eff} effect (Maeder & Meynet 2000).

Rotation is a key parameter besides M & Z (Maeder & Meynet 2000).

Thus, stars can only be modelled properly in multi-dimensions.



Potter, Chitre & Tout (2012)

The rotationally-driven dynamo model reproduces observed N enrichment in two distinct populations of massive stars observed in the LMC (VLT–FLAMES survey).
More massive stars: cannot support a dynamo are enriched by rotational mixing
Lower-mass stars: spun down rapidly and are enriched by magnetic mixing.

Applications (i) – cont'd.

State-of-the-art

1. 1D codes simplifications:

- The first models assumed solid body rotation Ω = cnst.
- Differential rotation: $\Omega(r)$ = cnst on isobars (shellular rotation).
- modelling meridional circulation: advective or diffusive, free parameters

2DStars will fill this void

2. 2D codes:

- Roxburgh (2004): non-evolving uniformly-rotating models
- Li+ (2009): solar models but on short timescales
- ROTORC (Dupree 1990) : only models main-sequence stars on short timescales
- ESTER (Espinosa Lara & Rieutord 2013): predicts pulsation frequencies of main-sequence stars

3. 3D codes:

- Djehuty (Dearborn+ 2006): hydrodynamical code (ideal for rapid phenomena but not to evolve a star).

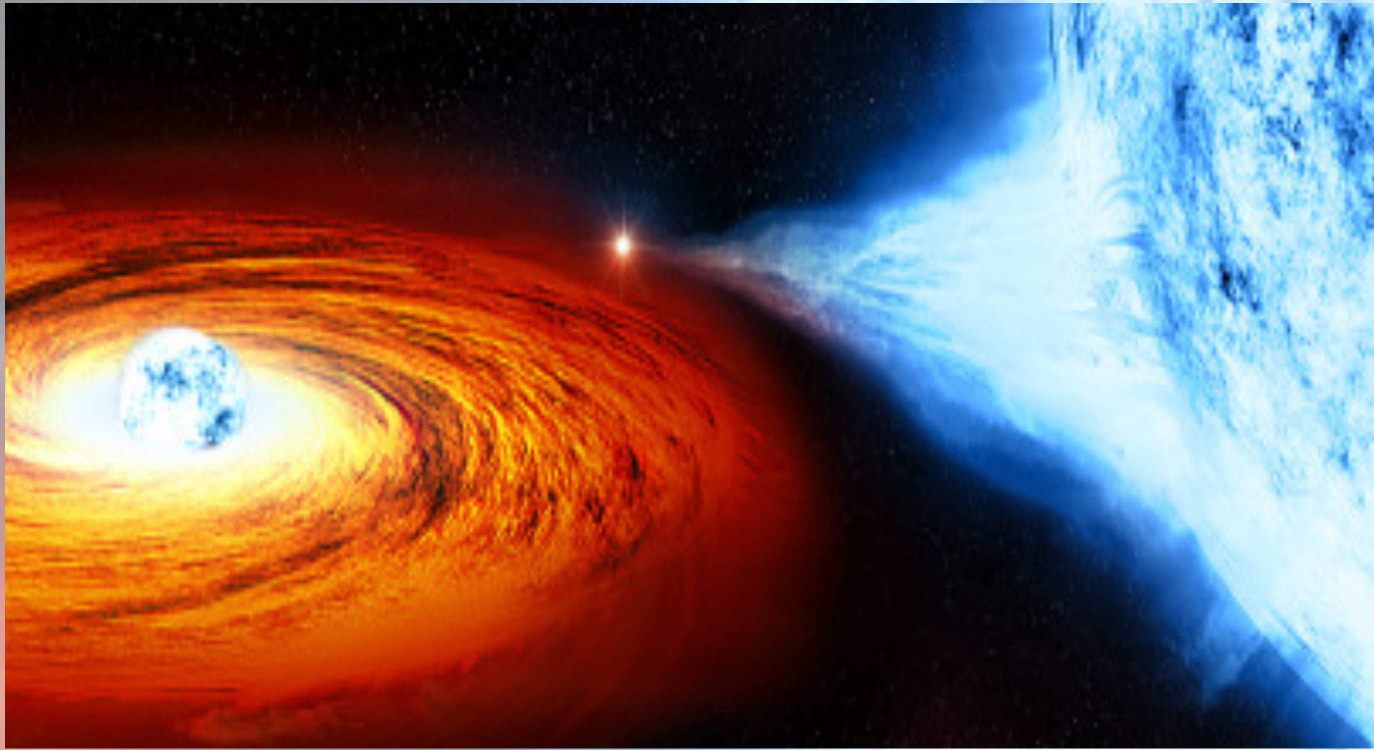
Applications (ii)

Mass Transfer in Close Binaries

Formation of an **accretion disc** by Roche-lobe overflow from the giant companion star.

Scott (2000) suggested that oblate distortion of rotating WDs drive **latitude-dependent** abundance gradients that may affect dust formation following a nova ejection **(prolate ejecta?)**.

2D models may provide important feedback on the accretion process preceding the synthesis of C-rich dust in CO nova ourbursts **(Jordi José, G. M. Halabi & Mounib El Eid 2016 A&A (accepted))**



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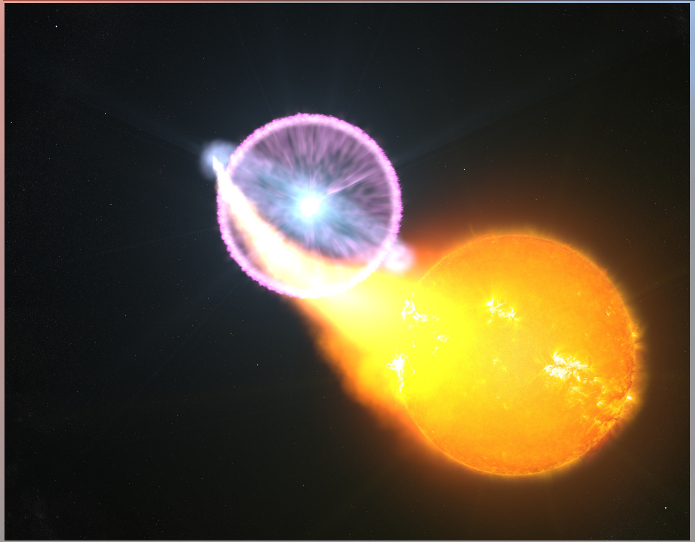


S. Wiessinger/Nasa Goddard Space Flight Center

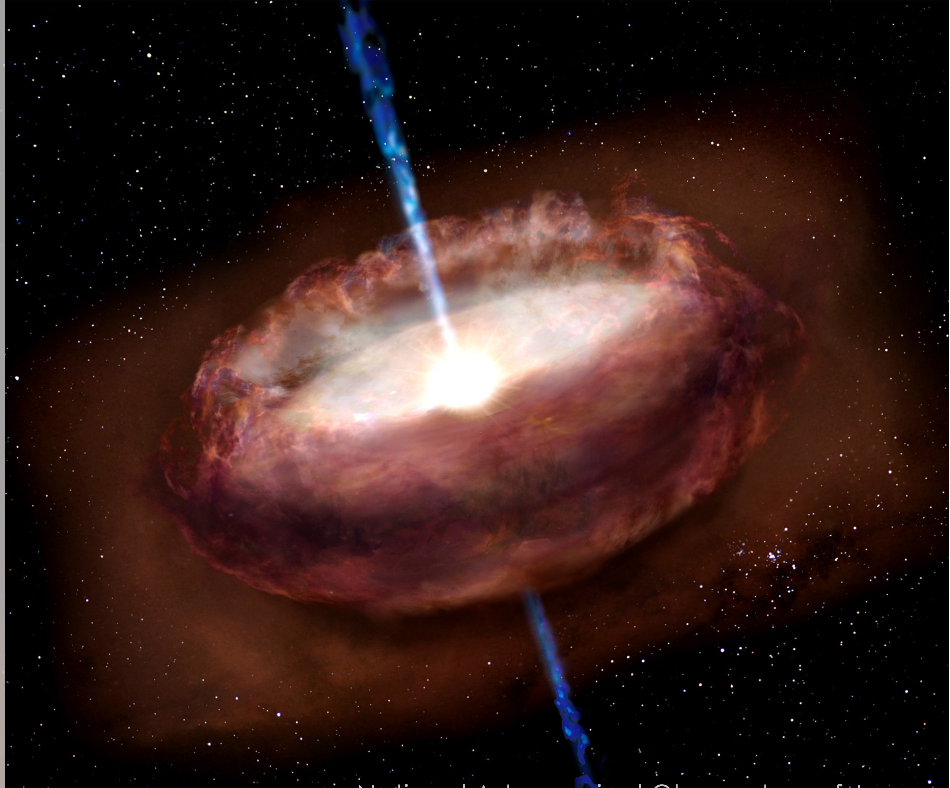
Applications (iii)

Star formation: Jets and Accretion Discs

A protoplanetary disc around young star *RY Tau* and infrared image of protostar *L1527*:

Both have rapidly spinning stars and discs which are magnetically connected and launch high-energy jets.

The star spins faster than the disc, twisting and shearing the magnetic field, storing up energy. Transition to a stable state unleashes stored energy in X-ray blasts.



National Astronomical Observatory of Japan

Spitzer Space Telescope, Tobin/NASA/JPL-Caltech

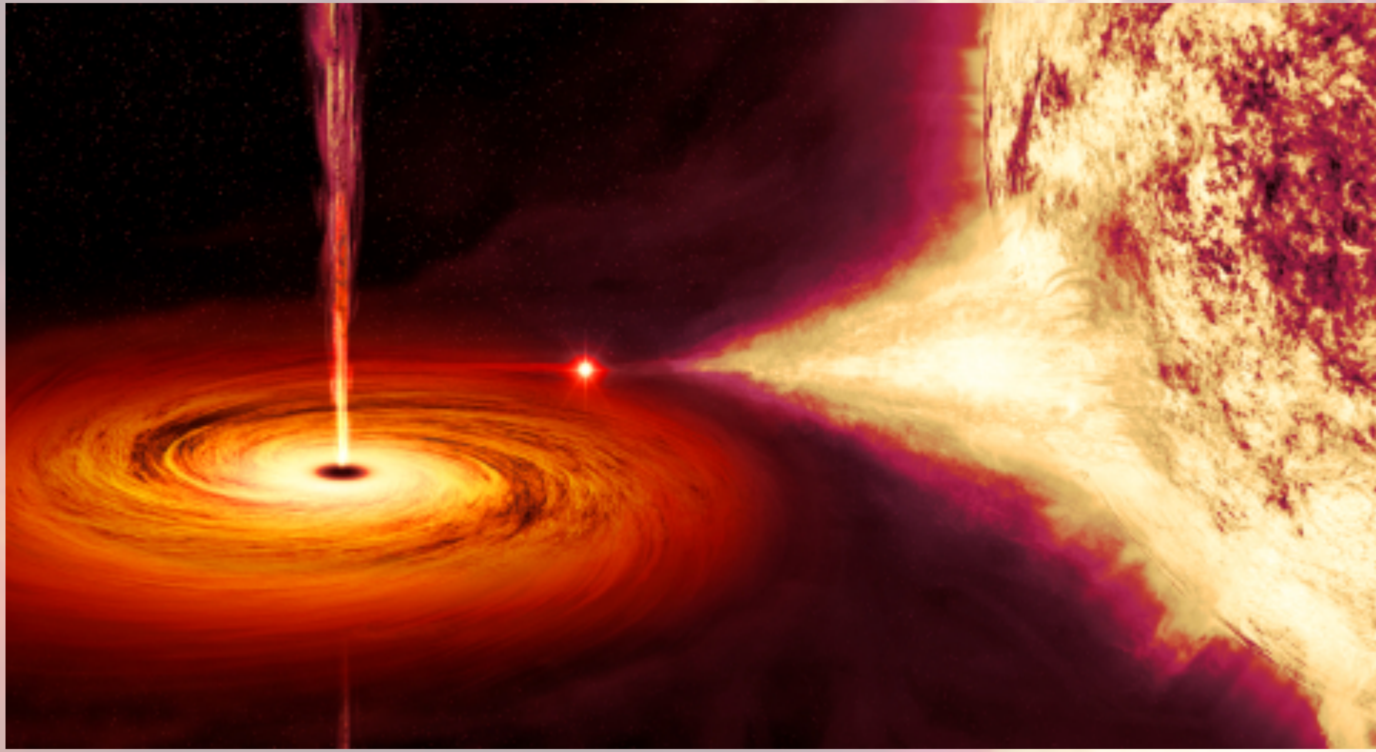
Applications (iv)

Tidally-Locked X-ray Binary Systems

V404 Cygni is a low-mass X-ray binary system that consists of a black hole and a star similar to our Sun.

The gas ripped from the star by tidal forces heats to millions of degrees as it falls inwards to the black hole.

A steady stream of high-energy radiation is emitted.



http://www.cfa.harvard.edu

Input physics

- ***Rotation:*** Slow internal fluid rotation-driven flows including meridional circulation will be modelled consistently.
- ***Magnetic fields:*** They enforce co-rotation and couple stellar cores to their envelopes. Only in at least 2D can this be done self-consistently with angular momentum transport.
- ***Chemistry:*** Slow internal mixing will be fully incorporated. Fast mixing (convection, horizontal turbulence…) will be parameterized.
- ***Mass transfer:*** Tides and mass transfer in binaries can spin stars to their critical breakup limit. Material accretes through an accretion disc which should be modelled in 2D.

Initial setup

- ★ A **Single rotating star** that evolves in time, for a given set of initial conditions.
- ★ We are interested in the **long term** (nuclear/thermal time scale) evolution i.e. that of the order of the stellar lifetime.
- ★ We **ignore magnetic fields** for now.
- ★ The star is **axisymmetric.** This symmetry can be broken by:
    1. Magnetic fields (e.g. O & B stars (Donati+ 2006, Grunhut+ 2012), Ap & Bp stars (Hubrig+ 2005)): Ignoring magnetic fields is not too bad for stars like Vega (Lignieres+ 2009, Petit+ 2010).
    2. Non-axisymmetric deformation of the stellar surface in Roche lobe-filling systems by external irradiation of the secondary by a close compact companion (X-ray binaries, binary pulsar systems ..). This is a 3D problem (Philips & Podsiadlowski 2002).

Specifics of the code

- **Programming language: JAVA** (portability, garbage collection, performance, build)
- **Discretization scheme: Finite difference**
- **The physics**
- **Grid structure**

The physics

Discretized equations of stellar structure:

Continuity equation:

$$\mathrm{div}\,(\rho\vec{v}) = 0$$

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\rho u) + \frac{1}{r sin\theta}\frac{\partial}{\partial\theta}(sin\theta\rho v) = 0$$

Momentum equation:

r-component:

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\rho u^2) + \frac{1}{r sin\theta}\frac{\partial}{\partial\theta}(sin\theta\rho uv) - \rho\frac{u^2+w^2}{r} = -\frac{\partial P}{\partial r} - \rho\frac{\partial\psi}{\partial r}$$

θ-component:

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\rho uv) + \frac{1}{r sin\theta}\frac{\partial}{\partial\theta}(sin\theta\rho v^2) + \rho\frac{uv}{r} - \frac{cot\theta\rho w^2}{r} = -\frac{1}{r}\frac{\partial P}{\partial\theta} - \frac{\rho}{r}\frac{\partial\psi}{\partial\theta}$$

φ-component:

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\rho uw) + \frac{1}{r sin\theta}\frac{\partial}{\partial\theta}(sin\theta\rho vw) + \rho\frac{uw}{r} + \frac{cot\theta\rho wv}{r} = 0$$

Poisson equation:

$$\frac{\partial^2\psi}{\partial r^2} + \frac{2}{r}\frac{\partial\psi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\psi}{\partial\theta^2} + \frac{cot\theta}{r^2}\frac{\partial\psi}{\partial\theta} = 4\pi G\rho$$

What we have so far

A Well-structured 1D code that:

1. Solves the equations of stellar structure (hydrostatic equilibrium & Poisson equation) + polytropic equation of state, without considering energy generation and opacity. This is helpful since an analytical solution exists to test the code.

2. Is highly modular:
   - Integrator (Euler integrator, relaxation integrator)
   - Building models
   - Writing files
   - Constants
   - Visualizations

3. Can be easily modified to accommodate more complicated physics/solvers etc..

Currently underway…

- Upgrading the 1D code to **2D** (r, θ)
- Uniform mesh (in r and θ)

Next

- Consider a non-uniform mesh
- Adding energy transport equation. Consider fully convective case that incorporates transport coefficients in 2D (Jermyn, Tout, Chitre & Lesaffre)

Conclusions

- Many astrophysical phenomena require multi-D approaches. **2DStars** aims to provide such a framework.

- Most model output is affected by rotation by various degrees depending on rotational velocity (tracks in the HR diagram, lifetimes, masses, chemical composition…). Stellar evolution is thus a function of **M**, **Z** and **Ω**.

- A number of serious discrepancies between current models and observations have been noticed over the past few years (the distribution of stars in the HR diagram at various metallicities, He and N abundances in massive O- and B-type stars and in giants and supergiants..).

- The proliferation of physical formulations used to describe rotation requires **data** to constrain the models. The VLT–FLAMES survey of massive stars (Evans+ 2005, 2006), VLT–FLAMES Tarantula Survey (Evans 2011) and the ongoing Gaia-ESO Survey make such comparisons possible.