Leaves in the Wind:
The Variety of Radiative & MHD fluctuations in Rotating Solar/Stellar Outflows

Steven R. Cranmer
University of Colorado Boulder, LASP

A. A. van Ballegooijen, L. N. Woolsey, A. Schiff, S. Van Kooten, C. Gilbert, S. E. Gibson, C. E. DeForest, J. L. Kohl, S. Saar, M. P. Miralles, S. P. Owocki
Leaves in the Wind:
The Variety of Radiative & MHD fluctuations in Rotating Solar/Stellar Outflows

Outline:
1. The Sun: convection → coronal heating?
2. Cool stars: generalizing the solar case; accretion
3. Massive stars: radiation pressure & pulsations

Steven R. Cranmer
University of Colorado Boulder, LASP

A. A. van Ballegooijen, L. N. Woolsey, A. Schiff, S. Van Kooten, C. Gilbert, S. E. Gibson, C. E. DeForest, J. L. Kohl, S. Saar, M. P. Miralles, S. P. Owocki
Why do we care?

- Stellar winds affect how stars & galaxies evolve… from pre-main-sequence accretion to post-main-sequence “death” & mass recycling.

- Consequently, they affect the formation & habitability of **planets**, too.
**Why do we care?**

- Stellar winds affect how stars & galaxies evolve… from pre-main-sequence accretion to post-main-sequence “death” & mass recycling.

- Consequently, they affect the formation & habitability of **planets**, too.

- In our own solar system, “space weather” affects satellites, power grids, pipelines, and safety of astronauts & high-altitude airline crews.

- If you can understand how plasmas behave in turbulent, expanding stellar atmospheres, you’ll have a superb grounding in many fields.
Stellar winds across the H-R Diagram
Stellar winds across the H-R Diagram

Massive stars: radiation-driven winds
Stellar winds across the H-R Diagram

Massive stars: radiation-driven winds

Cool luminous stars: pulsation/dust-driven winds?
Stellar winds across the H-R Diagram

Massive stars: radiation-driven winds

Solar-type stars: coronal winds (driven by MHD turbulence?)

Cool luminous stars: pulsation/dust-driven winds?
1. The Sun: convection $\rightarrow$ coronal heating?

2. Cool stars: generalizing the solar case; accretion

3. Massive stars: radiation pressure & pulsations
Convection produces granulation

- Unstable convective overturning drives **p-mode** internal pulsation modes: largely evanescent at surface.

- The uppermost convection cells are visible as “granules,” and strong-field **magnetic flux tubes** are jostled (mostly) horizontally…

**Splitting / merging**

**Torsion**

**Bending** (kink-mode wave)

**Spruit (1984)**

**Longitudinal flow / wave**
Flux tubes (eventually) fill the corona

Analyzing some individual thin-tube oscillations has led to novel ways to measure the magnetic field (“coronal seismology”).

Flux tubes (eventually) fill the corona

Analyzing some individual thin-tube oscillations has led to novel ways to measure the magnetic field ("coronal seismology").

MHD waves expand out into the corona

With good instrumentation, imaging & spectroscopy can resolve plasma fluctuations in multiple ways...

• Intensity modulations . . .
  \[ \delta I \propto (\delta \rho)^{1-2} \]

• Motion tracking in images . . .
  \[ \delta V_{\text{POS}} \]

• Doppler shifts . . .
  \[ \delta \lambda \propto \delta V_{\text{LOS}} \]

• Doppler broadening . . .
  \[ \delta \lambda \rightarrow \langle \delta V_{\text{LOS}} \rangle \]

• Radio sounding . . .
  \[ \delta \tilde{n} \rightarrow \delta \rho, \delta B \rightarrow \delta V \]

• Transverse Alfvén waves dominate, with periods of order 3-5 minutes.
**Measured Alfvénic fluctuations**

- Cranmer & van Ballegooijen (2005) collected a range of observational data…

![Graph showing measured Alfvénic fluctuations](image-url)
Radiative & MHD fluctuations in Stellar Winds

Cranmer & van Ballegooijen (2005) collected a range of observational data...

- **Hinode/SOT**
- **SUMER & EIS**
- **Helios & Ulysses**
- **UVCS/SOHO**
- **EIS** (Hahn et al. 2013)

**Measured Alfvénic fluctuations**

- Undamped (WKB) waves
- Damped (non-WKB) waves

$r_{\text{m.s.}} \; \delta V_\parallel$ (km/s)

$(r/R_\odot) - 1$
Can turbulence explain coronal heating?

Convection shakes & braids magnetic field lines in a diffusive “random walk”

Alfvén waves propagate up...

...and they undergo an MHD turbulent cascade, from large to small eddies, eventually dissipating in intermittent stochastic “nanoflares”

Radiative & MHD fluctuations in Stellar Winds

S. R. Cranmer, GTP Workshop, Aug. 17, 2016
Can turbulence explain coronal heating?

• If the cascade is driven & time-steady, the rate of **stirring** should = rate of **cascade** = rate of **dissipation & heating**.

• MHD simulations inspire phenomenological scalings for the stirring/cascade rate:

\[
Q_{\text{heat}} \approx \frac{\rho v^3}{\ell} \approx \frac{\varepsilon \rho (v^2_{+}v_{-} + v^2_{-}v_{+})}{\ell_{\perp}}
\]

(e.g., Iroshnikov 1963; Kraichnan 1965; Strauss 1976; Shebalin et al. 1983; Hossain et al. 1995; Goldreich & Sridhar 1995; Matthaeus et al. 1999; Dmitruk et al. 2002; Chandran 2008)
Can turbulence explain coronal heating?

• If the cascade is driven & time-steady, the rate of \textbf{stirring} should = rate of \textbf{cascade} = rate of \textbf{dissipation & heating}.

• MHD simulations inspire phenomenological scalings for the stirring/cascade rate:

\[
Q_{\text{heat}} \approx \frac{\rho v^3}{\ell} \approx \frac{\varepsilon \rho (v^2_{+}v_{-} + v^2_{-}v_{+})}{\ell_{\perp}}
\]

• When plugged into self-consistent solutions for coronal heating & solar wind acceleration, it seems to work! (Cranmer et al. 2007).

• Including rotation produces realistic 3D structure (Cranmer et al. 2013).
Kinetic consequences…
Kinetic consequences…

Observing collisionless heating rates high up (e.g., UVCS/SOHO) reveals indirect information about how wave dissipation heats particles…

\[ T_{\text{ion}} \gg T_p \gtrsim T_e \, , \, T_- > T_+ \, , \, v_{\text{ion}} > v_p \]

- When eddies reach gyroradius scales, does the anisotropic cascade prefer:
  - ion cyclotron waves?
  - kinetic Alfvén waves?
  - magnetosonic whistlers?
Kinetic consequences…

Observing collisionless heating rates high up (e.g., UVCS/SOHO) reveals indirect information about how wave dissipation heats particles…

\[ T_{\text{ion}} \gg T_p \gtrsim T_e \ , \ T_{\perp} > T_{\parallel} \ , \ v_{\text{ion}} > v_p \]

- When eddies reach gyroradius scales, does the anisotropic cascade prefer:
  - ion cyclotron waves?
  - kinetic Alfvén waves?
  - magnetosonic whistlers?

Does the “wave” picture break down altogether when the turbulence is organized into coherent current sheets?
MHD waves generated “higher up?”

Not all coronal & solar wind fluctuations come directly from the solar surface…
Not all coronal & solar wind fluctuations come directly from the solar surface...

- The coronal magnetic field evolves via **magnetic reconnection** between ever-changing magnetic flux systems.

- Some forms of reconnection can launch MHD waves (Lynch et al. 2014; Moore et al. 2015).

- Strong shears between fast & slow solar wind (and CMEs!) can be unstable to wave growth via **Kelvin-Helmholtz instabilities** (Foullon et al. 2011; Ofman & Thompson 2011).
1. The Sun: convection $\rightarrow$ coronal heating?

2. Cool stars: generalizing the solar case; accretion

3. Massive stars: radiation pressure & pulsations
Applying turbulence theory to solar-type stars
Applying turbulence theory to solar-type stars

Observations

Cranmer & Saar (2011) Models

Sun

Radiative & MHD fluctuations in Stellar Winds

S. R. Cranmer, GTP Workshop, Aug. 17, 2016
Evolution of inflows & outflows

Accretion rate

Mass loss rate

T Tauri phase

Present-day Sun

Red giant

Mass gained or lost (Moons /yr)

AGE (Billions of years)
Young stars: 2 sources of turbulence

• T Tauri protostars are convectively unstable… they generate their own waves.
• But the accretion is variable! Clumps of plasma impact the star… and induce “externally driven” surface turbulence.
• Cranmer (2008, 2009) modeled the resulting winds & X-ray emission.

Impact-generated “ripples” are similar to EUV waves observed on the Sun after strong flares…
1. The Sun: convection → coronal heating?
2. Cool stars: generalizing the solar case; accretion
3. Massive stars: radiation pressure & pulsations
Massive star winds: radiative driving

- Castor, Abbott, & Klein (1975) worked out how a hot star’s radiation can accelerate a time-steady wind, even if gravity >> continuum radiation force.

- Spectral lines are the key! \[ a_{\text{rad}} = \int d\nu \frac{\kappa_\nu F_\nu}{c} \]

- Bound electron resonances have higher cross-sections than free electrons (i.e., spectral lines dominate the opacity \( \kappa_\nu \)).
Massive star winds: radiative driving

- Castor, Abbott, & Klein (1975) worked out how a hot star’s radiation can accelerate a time-steady wind, even if gravity >> continuum radiation force.

- Spectral lines are the key! \[ a_{\text{rad}} = \int d\nu \frac{\kappa_{\nu} F_{\nu}}{c} \]

- Bound electron resonances have higher cross-sections than free electrons (i.e., spectral lines dominate the opacity \( \kappa_{\nu} \))

- In the accelerating wind, narrow opacity sources become Doppler shifted with respect to star’s photospheric spectrum.

- Acceleration thus depends on velocity & velocity gradient! This turns “\( F=ma \)” on its head! (Nonlinear feedback...)
New forces → new wave modes

- Radiative acceleration is proportional to \((dv/dr)\) and wind density...

\[
g_{\text{CAK}} = g_{\text{CAK},0} + g_{\text{CAK},1} = g_{\text{CAK},0} + \frac{\partial v_1}{\partial r} \left[ \frac{\partial g_{\text{CAK}}}{\partial (dv/dr)} \right]_0 + \rho_1 \left[ \frac{\partial g_{\text{CAK}}}{\partial \rho} \right]_0
\]

Steeper gradients → stronger line forces. The Abbott (1980) speed \(U_A\) can be supersonic

usually neglected; important for low freq’s
**New forces → new wave modes**

- Radiative acceleration is proportional to \((dv/dr)\) and wind density…

\[
g_{\text{CAK}} = g_{\text{CAK},0} + g_{\text{CAK},1} = g_{\text{CAK},0} + \frac{\partial v_1}{\partial r} \left[ \frac{\partial g_{\text{CAK}}}{\partial (dv/dr)} \right]_0 + \rho_1 \left[ \frac{\partial g_{\text{CAK}}}{\partial \rho} \right]_0
\]

Steeper gradients → stronger line forces.
The Abbott (1980) speed \(U_A\) can be supersonic

usually neglected; important for low freq’s
New forces → new wave modes

- Massive stars undergo low-frequency pulsations. Do waves “leak out?”
- Proper treatment requires a non-WKB model of Abbott waves (Cranmer 2007).

Strongly **nonlinear** pulsations saturate; radiation forces produce “kinks” in $v(r)$
New forces $\rightarrow$ new wave modes

- For a rotating star with “spots,” the nonlinear kinks produce corotating interaction regions (CIRs).

- CIRs appear to be visible in spectral lines formed in rotating winds (Cranmer & Owocki 1996).
New forces $\rightarrow$ new wave modes

- For a rotating star with “spots,” the nonlinear kinks produce **corotating interaction regions (CIRs)**.
- CIRs appear to be visible in spectral lines formed in rotating winds (Cranmer & Owocki 1996).

- A more accurate treatment of the radiation force shows that small wavelengths are **strongly unstable** to rapid growth (Owocki & Rybicki 1984, 1985, 1986, …)
- The resulting shocks appear to explain **X-rays** seen around most O stars.
Conclusions

• Waves are excellent diagnostics of stellar outflows.

• Within an order of magnitude, theories aren’t doing too badly in predicting observed properties of solar & stellar winds.

• However, there’s still much to do . . .

• Understanding is greatly aided by ongoing collaboration between the solar physics, plasma physics, and astrophysics communities.