Anomalous hydrodynamics kicks neutron stars

AstroCoffee, ITP Frankfurt, 15.12.2015

Matthias Kaminski
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[Kaminski, Uhlemann, Schaffner-Bielich, Bleicher; (2014)]
Chiral hydrodynamics & neutron star kicks

observation: neutron stars undergo a large momentum change (a kick)
Chiral hydrodynamics \& neutron star kicks

hydrodynamics: fluids with left-handed and right-handed particles produce a current along magnetic field

e.g. right/left-handed electrons, neutrinos, ...

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\[ \vec{B} \]

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Chiral hydrodynamics leads to neutron star kicks

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observation: neutron stars undergo a large momentum change (a kick)
Outline

✓ Invitation: chiral hydrodynamics & neutron star kicks

1. Neutron star observations

2. Previous kick mechanisms

3. Sophisticated simulations

4. Chiral hydrodynamics

5. Kicks from anomalies

6. Observable signals?
1. Observations
Neutron stars kicked out of their initial position with velocities ~ 1000 km/s
Kick observations

Neutron stars kicked out of their initial position with velocities ~ 1000 km/s

[Chatterjee et al.; Astrophys. J (2005)]
Neutron stars kicked out of their initial position with velocities $\sim 1000 \text{ km/s}$

Neutron stars kicked out of their initial position with velocities ~ 1000 km/s

[Chatterjee et al.; Astrophys. J (2005)]
Kick observations

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Neutron star genesis

- compact star
  * small radius
  * large mass
  * high density
- supernova remnant
- quick rotation
- large B field
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naive picture a short time interval immediately after the explosion: “crust”

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naive picture a short time interval immediately after the explosion: “crust”

proto-neutron stars are dense objects with “crust” and preferred directions
2. Previous kick mechanisms
Two categories of kick mechanisms
Something has to cause an asymmetry in the momentum distribution.

1.) asymmetric supernova explosion

2.) asymmetric emission of matter
Two categories of kick mechanisms
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Two categories of kick mechanisms
Something has to cause an asymmetry in the momentum distribution.

1.) asymmetric supernova explosion
   - kicks of about 1000 km/s  
   - random seed perturbations plus hydro instabilities (SASI)
   - hydro model, neutrino transport, boundary cond’s
   - timescale: ~5 seconds

2.) asymmetric emission of matter
   - neutrino emission [Vilenkin (1978)]
   - beyond the standard model [Fuller, Kusenko, Mocioiu, Pascoli (2003)]
   - neutrino kicks, nucl-th [Sagert, Schaffner-Bielich (2007)]
Two categories of kick mechanisms
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Problems with previous kick mechanisms

ad 1.) asymmetric supernova explosion
  ‣ kick may be too small
  ‣ numerical analysis, no analytic understanding
  ‣ no magnetic dipole fields, no chiral hydro
  ‣ instabilities disturbed by other hydro effects?

ad 2.) asymmetric emission of matter
  ‣ neutrino kick too small
  ‣ neutrinos too cold
  ‣ microscopic asymmetry washed out [Kusenko, Segre, Vilenkin (1998)]
  ‣ need physics beyond the standard model

[Fuller, Kusenko, Mocioiu, Pascoli (2003)]
Problems with previous kick mechanisms

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   [Fuller, Kusenko, Mocioiu, Pascoli (2003)]

Our anomalous hydrodynamic formalism addresses and overcomes these problems.
3. Sophisticated simulations
First 10 seconds inside proto-neutron stars

- baryonic matter: 10 km radius
- neutrinos: last scattering surfaces around 10 km
- no anti-neutrinos
- only electron flavor inside 10 km
- high densities
- neutrinos trapped! (everything trapped)

cf. [Wongwathanarat, Janka, Muller; (2012)]
First 10 seconds inside proto-neutron stars
[Fischer et al.; PRD (2011)]
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confirms our naive picture;
apply hydrodynamics!
We are not interested in signals at infinity.
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[ measured far away from star ]

[Fischer et al.; PRD (2011)]

proto-neutron star

Earth
We are not interested in signals at infinity.

[Fischer et al.; PRD (2011)]
4. Chiral hydrodynamics
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Hydrodynamic variables

Thermodynamics

\[ T, \mu, u^\nu \]

Hydrodynamics

\[ T(t, \vec{x}), \mu(t, \vec{x}), u^\nu(t, \vec{x}) \]
Hydrodynamic variables

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thermodynamic variables: temperature, chemical potential, velocity

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Hydrodynamics

\[ T(t, \vec{x}), \mu(t, \vec{x}), u^\nu(t, \vec{x}) \]

hydrodynamic fields
Hydrodynamics
universal effective field theory, expansion in gradients of temperature, chemical potential and velocity

- fields \( T(x), \mu(x), u^\nu(x) \)
- conservation equation
  \[ \nabla_\nu j^\nu = 0 \]
- constitutive equation (Landau frame)
Hydrodynamics

universal effective field theory, expansion in gradients of temperature, chemical potential and velocity

• fields \( T(x), \mu(x), u^\nu(x) \)

• conservation equation

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continuity: \( \partial_t n + \vec{\nabla} \cdot \vec{j} = 0 \)

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Hydrodynamics

universal effective field theory, expansion in gradients of temperature, chemical potential and velocity

• fields $T(x), \mu(x), u^\nu(x)$

• conservation equation

$$\nabla_\nu j^\nu = 0$$

continuity: $\partial_t n + \vec{\nabla} \cdot \vec{j} = 0$

• constitutive equation (Landau frame)

Conserved current

$$j^\mu = n u^\mu + \nu^\mu$$

Form can be derived and restricted from first principles. [Landau, Lifshitz]
Chiral hydrodynamics

Derived for any theory with **chiral anomaly** (e.g. the standard model of particle physics)

\[ \nabla_\nu j^\nu = 0 \quad \text{classical theory} \]

[Son, Surowka; PRL (2009)]
[Loganayagam; arXiv (2011)]
Chiral hydrodynamics

Derived for any theory with chiral anomaly

\[ \nabla_{\mu} j^{\mu} = C \epsilon^{\nu\rho\sigma\lambda} F_{\nu\rho} F_{\sigma\lambda} \]

quantum theory

(e.g. the standard model of particle physics)
Chiral hydrodynamics

Derived for any theory with **chiral anomaly**
(e.g. the standard model of particle physics)

\[ \nabla_\mu j^\mu = C \epsilon^{\nu\rho\sigma\lambda} F_{\nu\rho} F_{\sigma\lambda} \]

Generalized constitutive equation with external fields:

\[
\begin{align*}
    j^\mu &= n u^\mu + \sigma E^\mu + \sigma^B B^\mu + \sigma^V \omega^\mu + \ldots \\
    \text{(non)} &\quad \text{(ideal)} \\
    \text{conserved} &\quad \text{charge} \\
    \text{current} &\quad \text{flow} \\
    \text{conduc-} &\quad \text{magnetic} \\
    \text{tivity} &\quad \text{field term} \\
    \text{term} &\quad \text{vorticity} \\
    \text{term} &\quad \text{term}
\end{align*}
\]

Agrees with gauge/gravity prediction
[Erdmenger, Haack, Kaminski, Yarom; JHEP (2009)]
Chiral hydrodynamics

Derived for any theory with chiral anomaly (e.g. the standard model of particle physics)

Generalized constitutive equation with external fields:

\[ j^\mu = n u^\mu + \sigma E^\mu + \sigma^B B^\mu + \sigma^V \omega^\mu + \ldots \]

Chiral magnetic conductivity:

\[ \sigma^B = C \mu \]

Anomaly-coefficient C
Chiral hydrodynamics

Derived for any theory with chiral anomaly (e.g. the standard model of particle physics)

\[ \nabla_\mu j^\mu = C \epsilon^{\nu\rho\sigma\lambda} F_{\nu\rho} F_{\sigma\lambda} \]

Generalized constitutive equation with external fields:

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Chiral magnetic conductivity:

\[ \sigma^B = C \mu \]

Observable in:

heavy ion collisions?

[Kharzeev, Son.; PRL (2011)]

neutron stars?

[Kaminski, Uhlemann, Schaffner-Bielich, Bleicher; (2014)]

Agrees with gauge/gravity prediction

[Erdmenger, Haack, Kaminski, Yarom; JHEP (2009)]
Chiral effects in various currents

[Neiman, Oz; JHEP (2010)]

More than one anomalous current

Constitutive relation:

\[
\left< \partial_\mu J^\mu_a \right> = \frac{1}{8} C_{abc} \epsilon^{\mu\nu\rho\sigma} F^b_\mu F^c_\rho \]

\[
J^\mu_a = n_a u^\mu + \sigma_a^b V_b^\mu + \sigma_a^V \omega^\mu + \sigma_{ab}^B B^b_\mu + O(\partial^2)
\]

Chiral magnetic conductivity:

\[
\sigma_{ab}^B = C_{abc} \mu^c
\]

various charges
(e.g. lepton number, electromagnetic charge, ...)
5. Kicks from hydrodynamics

\[ \sum_{i} \vec{p}_i \rightarrow \text{emitted neutrinos} \]

\[ \vec{B} \]

\[ \vec{p}_{\text{ns}} \]
Relevant currents in neutron stars
[Kaminski, Uhlemann, Schaffner-Bielich, Bleicher; (2014)]

A bucket full of electrons and electron neutrinos with short mean free path

\[ B = 0.1 \text{MeV}^2 \]
\[ \mu^\ell \approx 300 \text{MeV} \]
A bucket full of electrons and electron neutrinos with short mean free path

Microscopic (standard model) currents: axial/lepton/EM:

\[ J_{\ell_5}^\mu = \bar{e}_L \gamma^\mu e_L - \bar{e}_R \gamma^\mu e_R + \bar{\nu}_L \gamma^\mu \nu_L \]

\[ J_{\ell}^\mu = \bar{e}_L \gamma^\mu e_L + \bar{e}_R \gamma^\mu e_R + \bar{\nu}_L \gamma^\mu \nu_L \]

\[ J_{EM}^\mu \]
Relevant currents in neutron stars

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\[ J_{\ell}^\mu = \bar{e}_L \gamma^\mu e_L + \bar{e}_R \gamma^\mu e_R + \bar{\nu}_L \gamma^\mu \nu_L \]
\[ J_{EM}^\mu \]

Macroscopic (hydrodynamic) description:

\[ J_a^\mu = n_a u^\mu + \sigma_a^b V_b^\mu + \sigma_a^V \omega^\mu + \left( \sigma_{ab}^B B_b^\mu \right) + O(\partial^2) \]
\[ \sigma_{ab}^B = C_{abc} \mu^c \]
Estimate of the neutron star kick

A bucket full of electrons and electron neutrinos with short mean free path

\[ B = 0.1 \text{MeV}^2 \]
\[ \mu^\ell \approx 300 \text{MeV} \]
\[ \langle p_\nu \rangle \approx \mu^\ell. \]

\[ \sum_i \vec{p}_i \] emitted neutrons

\[ \vec{B} \]

\[ \sigma^B_{ab} = C_{abc} \mu^c \]
Estimate of the neutron star kick

A bucket full of electrons and electron neutrinos with short mean free path

\[ \sum_i \vec{p}_i \]

\[ \vec{B} \]

\[ \sigma_{ab}^B = C_{abc} \mu^c \]

e.g.:
\[ C_{\ell,\ell,5,EM} = \frac{1}{2\pi^2} \]

\[ B = 0.1 \text{ MeV}^2 \]

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[Kaminski, Uhlemann, Schaffner-Bielich, Bleicher; (2014)]

A bucket full of electrons and electron neutrinos with short mean free path

\[
\sigma_{ab}^B = C_{abc} \mu^c
\]

Chiral conductivity:

\[
\sigma_{\ell 5, EM}^B = C_{\ell, \ell 5, EM} \mu^\ell
\]

e.g.:

\[
C_{\ell, \ell 5, EM} = \frac{1}{2\pi^2}
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Chiral conductivity:

\[ \sigma_{\ell,5,EM}^B = C_{\ell,\ell5,EM} \mu^\ell \]

Axial lepton current:

\[ \vec{J}_{\ell5} = C \mu^\ell \vec{B} \approx \vec{e}_B \cdot 1 \text{ MeV}^3 \]

\[ \sigma^B_{ab} = C_{abc} \mu^c \]

E.g.:

\[ C_{\ell,\ell5,EM} = \frac{1}{2\pi^2} \]
Estimate of the neutron star kick

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\[ B = 0.1 \text{MeV}^2 \]
\[ \mu^{\ell} \approx 300 \text{MeV} \]
\[ \langle p_\nu \rangle \approx \mu^{\ell} \]

Chiral conductivity:
\[ \sigma^B_{\alpha \beta} = C_{\alpha \beta \gamma} \mu^\gamma \]
\[ \sigma_{\ell 5, EM} = C_{\ell, \ell 5, EM} \mu^{\ell} \]

Axial lepton current:
\[ \vec{J}_{\ell 5} = C \mu^{\ell} \vec{B} \approx \vec{e}_B \cdot 1 \text{MeV}^3 \]

Particle flux and momentum transfer:
\[ \dot{N}_\nu = |\vec{J}| A_{\text{surface}} \]
\[ \Delta P_{\text{NS}} = \Delta t \dot{N}_\nu \langle p_\nu \rangle \]
\[ \Delta t \approx 10 \text{s} \]
Estimate of the neutron star kick

A bucket full of electrons and electron neutrinos with short mean free path

\[ \frac{B}{B_{\text{NS}}} = \frac{C_{\text{abc}}}{\mu^c} \]

Chiral conductivity:

\[ \sigma_{\ell 5, EM} = C_{\ell, \ell 5, EM} \mu^\ell \]

Axial lepton current:

\[ \vec{J}_{\ell 5} = C \mu^\ell \vec{B} \approx \epsilon B \cdot 1 \text{ MeV}^3 \]

Particle flux and momentum transfer:

\[ \dot{N}_\nu = |\vec{J}| A_{\text{surface}} \]

Neutron star mass:

\[ m_{\text{NS}} = 3 \cdot 10^{30} \text{ kg} \]
Estimate of the neutron star kick

[Kaminski, Uhlemann, Schaffner-Bielich, Bleicher; (2014)]

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\[ B = 0.1 \text{ MeV}^2 \]
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\[ m_{NS} = 3 \cdot 10^{30} \text{ kg} \]

Kick velocity agrees with observations:
\[ \Rightarrow \quad v_{\text{kick}} \approx 1000 \frac{\text{km}}{\text{s}} \]
6. Observable signals?
Observable signal?
Observable signal?

Prediction: Kick magnitude depends on angle between rotation axis and internal magnetic field axis.

For fast spinning neutron stars, kick directed along rotation axis.
Observation: neutron stars undergo a large momentum change (a kick).

Summary

- Anomalous hydrodynamics leads to neutron star kicks.
  - fluids with left-handed and right-handed particles produce a current along magnetic field.

Outlook

- check with simulation
- kick aligned with spin?
- determine B from kick
- measure gravitational anomaly?
Summary

Anomalous hydrodynamics leads to neutron star kicks

-Kaminski, Uhlemann, Schaffner-Bielich, Bleicher; (2014)

- check with simulation
- kick aligned with spin?
- determine $B$ from kick
- measure gravitational anomaly?

Outlook
- further implications of chiral effects

Observation: neutron stars undergo a large momentum change (a kick)

Hydrodynamics: fluids with left-handed and right-handed particles produce a current along magnetic field
Come visit the University of Alabama, Tuscaloosa
http://bama.ua.edu/~mkaminski3/UA_Workshop_2015/Overview.htm
APPENDIX: chiral effects in vector/axial currents

see e.g. [Jensen, Kovtun, Ritz; JHEP (2013)]

Vector current (e.g. QCD U(1))

\[ J^\mu_V = \cdots + \xi_V \omega^\mu + \xi_{VV} B^\mu + \xi_{VA} B^\mu_A \]

chiral magnetic effect

Axial current (e.g. QCD axial U(1))

\[ J^\mu_A = \cdots + \xi \omega^\mu + \xi_B B^\mu + \xi_{AA} B^\mu_A \]

chiral vortical separation effect
APPENDIX: chiral effects in vector/axial currents

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Vector current (e.g. QCD U(1))

\[ J_V^\mu = \cdots + \xi_V \omega^\mu + \xi_{VV} B^\mu + \xi_{VA} B_A^\mu \]

chiral magnetic effect

Axial current (e.g. QCD axial U(1))

\[ J_A^\mu = \cdots + \xi_\omega \omega^\mu + \xi_B B^\mu + \xi_{AA} B_A^\mu \]

chiral vortical separation effect
APPENDIX: chiral effects in vector/axial currents

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\[ J_A^\mu = \cdots + \xi \omega^\mu + \xi_B B^\mu + \xi_{AA} B_A^\mu \]

chiral
magnetic
effect

chiral
evortical
effect

chiral
separation
effect

see e.g. [Jensen, Kovtun, Ritz; JHEP (2013)]