New Views on Coronal Mass Ejections from SDO, STEREO and Numerical Modeling

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C. Möstl (Graz) K. Shibata (Kyoto U.)

ISR, Boston College, Oct 23, 2012
Outline

Introduction: CMEs, space weather and coronagraphs.

Flux ropes and CMEs.
- Relationship: are all flux ropes CMEs? do flux ropes pre-exist CMEs?,
- How do flux ropes appear in the heliosphere?

Recent progress in predicting CME arrival time and direction.

Non-ideal evolution of CMEs
- Interchange reconnection,
- Deflection, rotation and expansion.

Multiple and interacting CMEs:
- (1) Numerical simulations,
- (2) Case study for the January 2007 events,
- (3) Recent remote-sensing studies shedding new light to CME-CME interaction.

Conclusion.
Coronal mass ejections at the Sun and their effects

CMEs can be identified in coronagraphs:
- Field-of-view is < 15% of the Sun-Earth distance.
- Measurements of Thomson scattered light:
  - Some sort of column density with geometrical factors.
- Speed varies from ~200 km/s to 3000 km/s
- Rate varies with solar cycle from 3 per week to 4 per day.
- Major cause of space weather.
Why focusing on CMEs?

About 80-90% of intense geomagnetic storms are caused by CMEs (Zhang et al., JGR, 2007; Echer et al., JGR, 2008).
- ~15% is caused by CIRs.
- 2/3 caused by single CMEs, 1/3 by multiple CMEs.

At least 2/3 of intense geomagnetic storms originate from active regions.

Gradual Solar Energetic Particle (SEP) events are associated with CME-driven shocks.

CMEs associated with type II (and others) radio emissions.

Space weather effects can be tracked into the heliosphere via aurora on the outer planets (Jupiter, Saturn) as shown in Prangé et al., Nature, 2004.

Why now? New observations with SDO (high cadence, new filters), STEREO (stereoscopic views, HIs) combined with in situ measurements and the development of large-scale, high-performance computer modeling.
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**Why now?** New observations with SDO (high cadence, new filters), STEREO (stereoscopic views, HIs) combined with *in situ* measurements and the development of large-scale, high-performance computer modeling.
Understanding in-situ measurements

- Magnetic cloud (Burlaga et al., 1981):
  - Smooth rotation of the magnetic field,
  - Low density, low temperature,
  - High magnetic field strength,
  - Low plasma beta.
  - Other possible characteristics (bidirectional electrons –BDEs–, charge states, composition).

- Understanding in-situ measurements for isolated CMEs via simulations:
  - Riley et al. 2002, Manchester et al., 2004, Cohen et al., 2007, Odstrcil et al., 2006.
  - Possible to start from a flux rope model at the Sun and obtain a magnetic cloud at 1 AU.
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Understanding in-situ measurements

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Interacting CMEs (1), (2), (3)
Beyond coronagraphs’ field-of-view

- Heliospheric Imagers (HIs) onboard STEREO (A & B) launched in late 2006.
- Basically same observations as coronagraphs but geometry is different.
- Can be complemented by radio emissions, interplanetary scintillation (IPS).
- STEREO FOV covers from Sun to Earth and beyond.

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T. Howard et al., *ApJ*, 2012a, b
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Flux ropes may be used to initiate CMEs in numerical models.

Flux ropes may be used to fit (stereoscopic) observations of CMEs.

Questions remain: Do all CMEs have flux ropes? Does the flux rope pre-exist?

Change in EUV imaging capabilities (EIT: ~12 min, EUVI: 2.5 min, SDO: 12 s).

Multi-spacecraft measurements (Messenger, VEX, STEREO, ACE/Wind).

Thernisien et al., SolPhys, 2009

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Recent insights about CMEs in the (low) corona

- SDO can detect the formation of CMEs prior to the eruption.  

- Advanced computer models can help us learn about the coupling between flux emergence sigmoids, and CMEs.


MHD model Simulated X-Ray

Roussev et al., Nat. Phys., 2012

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Jie Zhang et al., Nature Comm., 2012
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- Recent work using (multi-)spacecraft data point towards a “complicated” picture:
  - Reconstructions of same event observed at different spacecraft do not agree,
  - Length of field line outside and inside the cloud is similar: uniform twist?
  - Using 3 different codes, only about 30% of ICMEs are found to have consistent orientations.
- ICME profiles from MHD model with very limited twist can trick fitting models.

Jacobs et al., ApJL, 2009
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Observing the Sun-Earth Connection

- SECCHI with the Heliospheric Imagers allows for the tracking of CMEs and the imaging of the formation of CIRs from the Sun to the Earth.
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In the past 5 years, we had to develop the tools to analyze HI images:

- FP(F) assumes point-source like CME (Rouillard et al., 2008; Liu et al., 2010),
- HM(F) assumes self-similar expanded “attached” to the Sun (Lugaz et al., 2009; Lugaz, 2010),
- SSE assumes self-similar expansion with fixed angular width (Davies et al., 2012; Lugaz et al., 2010).

Tracks in J-maps have different shapes for different directions -> fitting methods.

Visual fitting by Wood et al., Byrne et al. + TH model of Tappin & T. Howard.
Importance of analysis techniques

- Difference in prediction/analysis between methods.
  - Change is usually minimal under optimal conditions (L4/L5).

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June 1, 2008 CME

Apr. 3, 2010 CME
Möstl et al., *GRL*, 2010

Feb. 13, 2009 CME
Heliospheric Imagers data can be used with real-time beacon data to improve CME hit/miss and arrival time forecasting (Davis et al., 2011).

Arrival time error decreases to about ± 6 hours with TH or fitting methods.

For fast CMEs, one can observe in real time the deceleration of the eruptions.

Citizen science through solarstormwatch.com (primarily UK researchers). Many of these fitting techniques are available there.

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**Table 2. Predicted ICME Arrival Times Compared With in Situ Measurements**

<table>
<thead>
<tr>
<th>Technique</th>
<th>Predicted Arrival at ACE</th>
<th>Predicted Arrival at Earth</th>
<th>Difference From in Situ Observation (h)</th>
<th>Lead Time of Prediction (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COR2 (geometric localization)</td>
<td>1740 UT ± 5 11 April 2010</td>
<td>0213 UT ± 1.18 12 April 2010</td>
<td>+5.43</td>
<td>2.16</td>
</tr>
<tr>
<td>HI</td>
<td>0113 UT ± 1.18 12 April 2010</td>
<td>0213 UT ± 1.18 12 April 2010</td>
<td>+12.98</td>
<td>2.0</td>
</tr>
<tr>
<td>Biesecker</td>
<td>0630 UT ± 8 11 April 2010</td>
<td>0630 UT ± 8 11 April 2010</td>
<td>-5.73</td>
<td>1.6</td>
</tr>
<tr>
<td>Enlil (SOHO/LASCO)</td>
<td>2100 UT 11 April 2010</td>
<td>2100 UT 11 April 2010</td>
<td>+8.75</td>
<td>0.6</td>
</tr>
<tr>
<td>Enlil (STEREO/COR2)</td>
<td>0900 UT 11 April 2010</td>
<td>0900 UT 11 April 2010</td>
<td>-3.25</td>
<td>0.6</td>
</tr>
<tr>
<td>STOA</td>
<td>0056 UT ± 12 11 April 2010</td>
<td>0056 UT ± 12 11 April 2010</td>
<td>-12.25</td>
<td>1.5</td>
</tr>
</tbody>
</table>

*All predictions, except for STOA refer to the ICME which was observed at L1 at 1214 UT on 11 April 2010.*
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CMEs at Large Angular Separation

How long will we be able to image Earth-directed CMEs with SECCHI?

Let’s look at STEREO-directed CMEs observed by STEREO/SECCHI:

Example: Dec. 4, 2009 CME observed remotely by ST- B and in situ by ST-A; A-B separation 130°, similar to ST-Earth separation in Dec. 2012.

December 2009

December 2012
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Predictions

**Arrival time at STEREO-A:**

- **FPF:** 12/09/2009 12:30 UT - Very glancing blow (33° away).
- **HMF** with correction from Möstl *et al.*, 2011 12/08/2009 18:20 UT - Direct hit (1.5° away).
- HMF works better in this case.

**About ten such back-sided events.**


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**Table 1:** Properties of backsided CMEs that have been observed by the STEREO/HIs

<table>
<thead>
<tr>
<th>No.</th>
<th>Date and Time of First Appearance</th>
<th>STEREO Separation</th>
<th>Heading Toward</th>
<th>Observed by</th>
<th>Maximum $\epsilon$</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2009 Jul 10 ~10UT</td>
<td>104:1</td>
<td>B(1)</td>
<td>HI-2A</td>
<td>27°</td>
<td>Lugaz <em>et al.</em>, 2011</td>
</tr>
<tr>
<td>2</td>
<td>2009 Jul 26 11:35</td>
<td>106:5</td>
<td>B(1)</td>
<td>HI-2A</td>
<td>38°</td>
<td>Lugaz <em>et al.</em>, 2011</td>
</tr>
<tr>
<td>3</td>
<td>2009 Sep 26 17:45</td>
<td>106:5</td>
<td>B(1)</td>
<td>HI-1A</td>
<td>15°</td>
<td>Lugaz <em>et al.</em>, 2011</td>
</tr>
<tr>
<td>5</td>
<td>2009 Nov 5 08:05</td>
<td>127:9</td>
<td>B(1)</td>
<td>HI-2A</td>
<td>24°</td>
<td>Lugaz <em>et al.</em>, 2011</td>
</tr>
<tr>
<td>7</td>
<td>2009 Dec 4 06:50</td>
<td>129:5</td>
<td>A(1)</td>
<td>HI-2B</td>
<td>32°</td>
<td>Lugaz <em>et al.</em>, 2011</td>
</tr>
<tr>
<td>9</td>
<td>2011 Nov 9 13:36</td>
<td>151:4</td>
<td>BE</td>
<td>HI-2A</td>
<td>42°</td>
<td>S. J. Tappin</td>
</tr>
<tr>
<td>10</td>
<td>2011 Nov 26 07:00</td>
<td>148:3</td>
<td>EA</td>
<td>HI-2B</td>
<td>36°</td>
<td>S. J. Tappin</td>
</tr>
</tbody>
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Lugaz *et al.*, *Sol Phys*, 2012


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Non-ideal evolution of CMEs: Anemone AR 10798

- CME evolution often deviates from self-similar and radial. What are the causes? Often CHs.

  - Observations and analyses reported in Asai et al., JGR, 2009.
  - Reconnection with background field results in drastic change of connectivity.

EIT movie courtesy C. Delannée
CME evolution often deviates from self-similar and radial. What are the causes? Often CHs.

Anemone active region = active region inside a coronal hole (CH), e.g. Shibata et al., *ApJ*, 1994.

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Interchange reconnection opens some of the erupting field lines.

After 10 min., there are open field lines embedded in closed field lines.


Opening-up of flux rope fields

Interchange Reconnection

Mix of open and closed field lines
Interchange reconnection opens some of the erupting field lines.

After 10 min., there are open field lines embedded in closed field lines.

Interchange reconnection opens some of the erupting field lines.

After 10 min., there are open field lines embedded in closed field lines.


Gosling et al., GRL, 1995

Crooker et al., JGR, 2008
The FR is deflected by about $10^\circ$ during the first 10 $R_{\text{Sun}}$ of propagation.

East deflection is consistent with the **Lorentz force** between the south current of the FR and the positive background open field.

Other ideas: fictious force, asymmetric expansion, channeling, B pressure & tension

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Cremades et al., *ASR*, 2006
Gopalswamy et al., *JGR*, 2009
Mohamed et al., *JGR*, 2012


Byrne et al., *Nat. Comm.*, 2010

see also C. Kay et al., *in prep.*

CME Rotation

**Causes:**

- Torque due to Lorentz force,
- Kink instability,

**Final results:**

- Aligned with HCS?
- Overshoot possible?
- What height does it stop?
- Heliospheric rotation?

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**In-situ**

- Imaging

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Isvanin *et al.*, 2012

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CME radial expansion is known from \textit{in situ} measurements at different distances (Helios). Bothmer & Schwenn found $r^{0.78}$; Liu \textit{et al.}, $r^{0.92}$.

Checked for the first time with SECCHI observations.

Bothmer & Schwenn, \textit{SSR}, 1994
Liu \textit{et al.}, \textit{PSS}, 2005
Gulisano \textit{et al.}, \textit{A&A}, 2010 & 2012
Savani \textit{et al.}, \textit{Ann. Geo.}, 2009
Savani \textit{et al.}, \textit{Sol Phys}, 2012
Nieves-Chinchilla \textit{et al.}, \textit{JGR}, 2012
Lugaz \textit{et al.}, \textit{ApJ}, accepted

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Shock inside a MC is one of the best way to produce strong Bz.

Nov 3-4, 2000 (Wang et al., GRL, 2003): 450 km/s halo then 1800 km/s halo

see also Burlaga et al., 2002

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Interacting CMEs

CME “cannibalism” and associated enhanced radio emissions were reported by Gopalswamy et al., *ApJ*, 2001.

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Studying complex ejecta properties at 1 AU

At Earth, the speed profile of the clouds is surprisingly uniform.

Not all ejecta at Earth are of the well-known magnetic cloud type, or even MC-like.

Two main questions:
- Final speed of the event,
- Evolution of the 2nd shock.

At Earth, the speed profile of the clouds is surprisingly uniform.

Interacting region between MCs characterized by high-$\beta$, lower $|B|$ and higher $T$. 

Wang, Yuming et al., 2003

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We performed a 3-D MHD simulation of 2 CMEs from the Sun to the Earth:

- CMEs initiated with identical flux rope-like structures 10 hours after each other,
- Tracked throughout the heliosphere. Goal: understand CME-CME interaction.

We find that the overtaking (faster) shock is essential to:

- homogenize the speeds between the two ejecta, and compress the first magnetic cloud.
- the final speed is determined by that of the faster ejection: NO traffic jam!

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Geo-effectiveness

- CME-CME interaction causes some of the most intense geo-effective storms.
- **Larger Bz**: due to compression of the 1st cloud.
- The long duration of the event (and the forcing) may result in increased geo-effectiveness.
- **Dense Sheath**: pre-condition the magnetosphere (fill the plasma sheet) before the arrival of the southward Bz period. This might be essential to explain the Dst (Farrugia et al. JGR, 2006).
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Complex ejecta
2000 November 24-25 homologous CMEs

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Dst ~ -70 nT, not very geo-effective

WHY?
Not well organized.

Wang et al., Sol Phys, 2002

http://pubpages.unh.edu/~nef32
Complex ejecta

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**Introduction**

- Flux Ropes and CMEs
- Space Weather Prediction
- Non-ideal Evolution
- Interacting CMEs (1) - Simulations

**Complex ejecta**

**2000 November 24-25 homologous CMEs**

**Burlaga et al., JGR, 2002**

**Wang et al., Sol Phys, 2002**


**Dst ~ -70 nT, not very geo-effective**

**WHY?**

Not well organized.
January 25, 2007 CME: fastest CME since SECCHI started imaging (1300 km/s).

Preceded by 16.5 hours by another, slower CME (650 km/s).

But **data gap** for ~ 18 hours after launch of the 2nd CME.
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Preceded by 16.5 hours by another, slower CME (650 km/s).
But data gap for ~ 18 hours after launch of the 2nd CME.
Numerical simulation of the 2007 January 24-25 CMEs

- Solar wind model of Cohen et al. (2007), out-of-equilibrium flux ropes chosen to match initial observed speed.
- From 1R_{Sun} to 1 AU: 40,000 $4^3$ blocks + 15,000 $8^3$ blocks (> 10M cells).
Detecting CME-CME interaction

- Synthetic COR2, HI1 and HI2 images.
- Ability to know what happened during data gap!
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T = 15:00:00 since January 24, 2007 00 UT

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J-maps of the events

Time (from 01/25)-elongation plots for PA 69 (apparent central PA of SECCHI).
Procedure developed by Sheeley et al. (1999) for LASCO data.


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BC/ISR - Oct. 23, 2012
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<th>Intermediate Step(s)</th>
<th>After Collision</th>
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<tr>
<td>No interaction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>v2 &gt; v1</td>
<td></td>
<td></td>
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<tr>
<td>Perfectly inelastic</td>
<td></td>
<td></td>
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<td>v2 &gt; v1</td>
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<tr>
<td>Mysterious collision</td>
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<td></td>
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<tr>
<td>v2 &gt; v1</td>
<td></td>
<td></td>
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<tr>
<td>Shock propagation</td>
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**No interaction does not explain the acceleration of the slower CME.**

**Inelastic collision is an unlikely explanation because v1 ≠ v2 after collision.**

**Mysterious process is required to explain observations.**

**Shock propagating through the first MC and dense sheath can explain the observations.**
Problem: density does not give a clear indication of the interaction.

Effect of the merging of shocks on the temperature, density, pressure and velocity.

As solar cycle 24 ramps up, multiple examples of CME-CME interaction:

- November 2008 CME (Chen, Wang et al., Nature Physics, 2012)

**Ability to directly image CME-CME interaction as it occurs with STEREO/SECCHI.**

STEREO-A  HI-1
2010-05-23 17:29UT
2 CMEs within about 10-15° and 21 hours from each other.

Large inclination -> low cross-section of interaction.

2010 May 23-24 CMEs

- 2 CMEs within about 10-15° and 21 hours from each other.
- Large inclination -> low cross-section of interaction.
Images and movies make it look like the 2 CMEs “passed” each other.

❖ J-maps for STEREO-A do not.
❖ J-maps for STEREO-B show a cannibalism.
❖ What did really happen?
difficulty of detecting interacting CMEs

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What did really happen?

http://pubpages.unh.edu/~nef32
Kinematics and Interaction

Position

- Front CME1
- Front MC1
- Front CME2
- Back MC1

Velocity

- Front CME2
- Front CME1
- Front MC1
- Back MC1

Widths

- CME
- Ejecta
- Sheath

Before interaction

\[ S \approx 0.3 r^{0.76} \]

CME2 catches up with CME1

CME2 decelerates

CME1 gets compressed

Widths

\[ S_{ICME} \approx 0.21r_{ICME}^{0.82} \]
**In-situ** measurements and deflection

- **In situ** data looks like an isolated CME.
- Consistent with deflection during interaction.
- Widths consistent with over-expansion after the CME-CME collision.

---

**Deflection angle vs. separation between 2 CMEs**

- **S\text{ICME, pred} = 0.21 AU**
- **S\text{ICME, meas} = 0.21 AU**

---

M. Xiong et al., *JGR*, 2009

Gulisano et al., *A&A*, 2010
2008 November 2-3 CMEs: super elastic?

2 CMEs within about 22 hours and 20° from each other.

Interaction lasted for ~16 hours, also resulted in small deflection.

Speeds before and after the interaction consistent with a 6% increase in the kinetic energy. Interaction likely to be super-elastic (73% probable).
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[Link](http://pubpages.unh.edu/~nef32)
Other studies of CME-CME interaction


Odstrcil et al., submitted


Fang Shen et al., JGR, 2011

M. Xiong et al., JGR, 2006-2009


http://pubpages.unh.edu/~nef32
Conclusions

The 2005-2015 decade has seen great advancements in remote-sensing observations of CMEs with SDO and STEREO.

CME and flux ropes:
- Flux rope is part of the cavity; it can be tracked through the heliosphere and associated with the MC.
- Some observations and measurements point towards a more complex picture.

CME rotation and deflection are due to magnetic forces acting on CMEs:
- MHD simulation of a CME from an anemone AR, one footpoint of the flux rope reconnects,
  - With streamer belt creating dimmings,
  - With open field resulting in a mix of closed and open magnetic field lines (consequence for BDEs).

Interacting CMEs are an important source of large geo-effective events:
- Increased geo-effectiveness due to compression of B and denser sheath.
- No traffic jam in space: slower CME accelerates wi
- CME-CME interaction can result in deflection, contraction, compression.
- Not yet possible to predict the type of ICME at 1 AU from SECCHI movies.
Thank you!

Thanks to Ilia Roussev, Chip Manchester, Tamas Gombosi, Carla Jacobs, Christian Möstl, Nada Alhaddad, Cooper Downs, Jorge Hernandez, Shibata-sensei, Angelos Vourlidas and Charlie Farrugia

*The studies have been made possible by the following grants:*

*NSF AGS0639335, AGS0819653, AGS1239699, AGS1239704 and NASA NNX08AQ16G and NNX12AB28G.*