Theory of G2 cloud multi-wavelength emission

The Cloudy Life of the Galactic Center
http://arxiv.org/abs/1309.2282

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G2 gas cloud (is it a cloud?)

Features:

- Emission broadly consistent with photoionized gas cloud with density $n \sim 3 \cdot 10^5 \text{cm}^{-3}$ and mass $M \sim 3M_{\text{Earth}}$
- Being tidally disrupted on the way towards Sgr A*
- Non-trivial radiative signatures are expected from pericenter passage and the accretion of debris
Observed luminosities and magnitudes

Line luminosities in different years: Brγ, Paα, HeI

Gillessen et al. 2013b

Gillessen et al. 2012

Broadband dust emission

Magnitudes in M and L’ bands, upper limit in Ks band in 2011

Observed 3 line luminosities in different epochs
+ 2 broadband luminosities
+ K-band upper limit or detection?

Line luminosities stay constant
Observed spatial extent and velocities

G2 is spatially extended w/ FWHM=42mas

Line widths give projected size $d=40-60$mas in 2008 and 2011 for new orbital parameters
talk by Leo Meyer

Gillessen et al. 2012

Scoville & Burkert 2013
Outline

0. Assume G2 is a cloud (no central source).
1. Compute ionizing radiation from nearby stars.
2. Dynamical models + radiative transfer.
3. Fit the observations => cloud properties.
4. Discuss emission from pericenter passage.
Ionizing continuum

All WR stars + reported bright stars + S0-2
(sample complete to $M \geq 10M_{\odot}$)

Lu+ 2009; Do+ 2013

Gillessen et al. 2009 – S0-2 star

Ionizing flux $F_{\text{ion}}$ vary little in 2004-2011 period

<table>
<thead>
<tr>
<th>Quantity</th>
<th>In 2004 at G2</th>
<th>In 2008 at G2</th>
<th>In 2011 at G2</th>
<th>At G2 pericenter</th>
<th>In 2011 at Sgr A*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from G2 to Sgr A*, arcsec ‡</td>
<td>0.59</td>
<td>0.43</td>
<td>0.30</td>
<td>0.020</td>
<td></td>
</tr>
<tr>
<td>Total flux*, $10^4$ erg s$^{-1}$ cm$^{-2}$</td>
<td>3.0 (75%)</td>
<td>3.5 (87%)</td>
<td>4.0 (100%)</td>
<td>5.7 (142%)</td>
<td>5.2 (129%)</td>
</tr>
<tr>
<td>S0-2 flux*, $10^4$ erg s$^{-1}$ cm$^{-2}$</td>
<td>0.26 (31%)</td>
<td>0.47 (57%)</td>
<td>0.84 (100%)</td>
<td>2.6 (306%)</td>
<td>2.0 (241%)</td>
</tr>
<tr>
<td>Total of IRS16NW, IRS16C, and IRS16SW</td>
<td>2.8 (86%)</td>
<td>3.1 (95%)</td>
<td>3.2 (100%)</td>
<td>3.2 (100%)</td>
<td>3.2 (100%)</td>
</tr>
<tr>
<td>fluxes*, $10^4$ erg s$^{-1}$ cm$^{-2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S0-2 contribution to flux</td>
<td>8.4%</td>
<td>13%</td>
<td>21%</td>
<td>44%</td>
<td>39%</td>
</tr>
</tbody>
</table>

How to reproduce constant $L(Br\gamma)$?

Cloud temperature is $T \sim 10^4 K$, above which cooling is substantial.

Temperature is constant over large range of heating rates

- Optically thin – the entire volume emits
  \[ L(Br\gamma) \sim n m_{cloud} T^{-1} \Rightarrow \text{constant density} \]

- Optically thick – reemits the absorbed light
  \[ L(Br\gamma) \sim F_{ion} S \Rightarrow \text{constant/slightly decreasing surface area} \]

G2 is always transparent in IR, but can have $\tau > 1$ to ionizing continuum: optically thick and optically thin cases

Only irradiated outer part of the cloud emits $Br\gamma$

A large amount of mass may be hidden from view!

Saitoh et al. 2013

Sutherland & Dopita (1993)
Dynamical models

Initially spherical cloud formed at 1” distance

Spherical cloud (preserves shape)

The spherical cow (in vacuum)

Tidally stretched

Unmagnetized tenuous cloud (nova/protoplanetary disk)

Magnetically arrested

Magnetized tenuous cloud (cooling stellar winds)

Magnetic pressure balances perpendicular gravity
Radiative transfer: CLOUDY code

Cloudy code [Ferland et al. 2013]
Version 13 released this year.

- All ionization and collisional processes for many atomic species.
- Various distributions and compositions of dust grains.
- Full radiative transfer from radio to hard X-rays.

Tested clouds with a large range of (initial) densities
Tested 10nm graphite dust and ISM size grain distribution
Modeling + results

Line luminosities/ratios

- $\text{Pa}\alpha/\text{Br}\gamma$ is always constant (same species)
- $\text{HeI}/\text{Br}\gamma$ is consistent w/ data for broad range of density $n_{2011} = 3 \cdot 10^4 - 10^7 \text{cm}^{-3}$
- Observed size => $n_{2011} > 6 \cdot 10^4 \text{cm}^{-3}$
- $\text{Br}\gamma$ line width is consistent

Gas properties

Broadband luminosities

Dust properties

- Small dust grains are self-consistently heated to $T=500K$
- ISM dust size distribution – a bit too red
- 10nm graphite grains – consistent L’-M color, predicts $m_{\text{Vega}}(K_s) = 19$

Temporal evolution

- Spherical optically thin and thick
- Tidally stretched optically thick ($100M_{\text{Earth}}$)
- Magnetically arrested optically thin and thick ($10-100M_{\text{Earth}}$)

- Not expected to preserve shape
- Tidal compression/ambient gas interaction => $L(\text{Br}\gamma)$ rises
- Hard to form a large cloud? => $10M_{\text{Earth}}$

Talk by Jorge Cuadra
Non-thermal emission at pericenter

Narayan et al. (2012); Sadowski et al. (2013a,b); Abarca et al. (2013)

However, “overly optimistic” assumptions:
... Large cloud cross-section radius $r=10^{15}$ cm
... Efficient particle acceleration

Sgr A*

Bow shock

G2

Bow shock accelerates particles => synchrotron radio/IR/X-ray emission

x-ray luminosity
\[ \nu L_\nu = 1.5 \times 10^{34} \left( \frac{\nu}{4 \text{keV}} \right)^{-0.1} \text{ erg s}^{-1} \]

Shcherbakov 2013

Actual observed fluxes are a factor of 20 lower

Bower et al. 2013
Non-thermal emission: reconciling theory and observations

1. Cloud is radially extended => bow shock at pericenter early? (late 2012/early 2013)  
   Radio/X-ray monitoring is continuous

2. Ambient density profile shallower than \( n \sim r^{-1} \)  
   Better density profile \( n \sim r^{-0.85} \) => 2x lower luminosity
   Shcherbakov et al. 2012; also Wang et al. 2013

3. Smaller cloud cross-section  
   Best-fitting perp. radius \( \rho = 4 \cdot 10^{14} \) cm => 5x lower luminosity  
   Shcherbakov 2013

4. Lower acceleration efficiency  
   Efficiency can readily be 1.5% => 3x lower luminosity  
   Narayan et al. 2012

5. Weak acceleration in oblique shocks  
   Effectively lower cross-section => lower luminosity  
   Sadowski et al. 2013a

Non-detection of non-thermal bow shock emission is consistent with the cloud hypothesis
Thermal emission at pericenter

Squeezing in perpendicular direction by
- shock driven by ambient gas (gradual)
- tidal compression (gradual)
- tidal compression shock (sudden)

Gas cools quickly =>
most emission is in IR lines/broadband

Saitoh et al. 2013; Ballone et al. 2013

Larger Brγ near pericenter, not observed
talk by Ballone

Magnetically arrested cloud

- Supported against ambient medium
- Weak tidal compression
- May only be weakly heated by B dissipation

May only exhibit a modest increase
in IR lines and broadband

Not actually observed

Gillessen et al. 2013a
What to expect after pericenter

Cloud mass is 4x larger => higher accretion rate?
But debris fallback is delayed
due to weaker interaction w/ ambient medium

- Magnetized cloud is less prone to Kelvin-Helmholtz instability
- Smaller cross-section and larger mass
- Ambient density is lower than used in numerical simulations

=> lower accretion rate, later onset

Numerical simulation
of magnetically arrested cloud
(is to be performed)
Conclusions

There is a scenario, which is
(1) self-consistent
(2) consistent with observations

Dynamics:
- spherical $10M_{\text{Earth}}$ cloud forms at 1” via runaway cooling of stellar winds
- cloud is magnetically arrested => little compression at pericenter
- delayed onset of fallback accretion

Radiation:
- reproduces $L(Br\gamma)$; $HeI/Br\gamma$; $Pa\alpha/Br\gamma$
- heated to $T=500K$ small dust reproduces magnitudes in $M$, $L'$, and $K_s(?)$
- non-thermal emission from bow shock is below detection threshold
- little/no thermal emission at pericenter

Looking forward to the bright future of G2