Recommendations for the Optimal NRAO Response to The G2 Encounter with Sagittarius A*

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June 29, 2012

1. Introduction and Recommendations

At the request of NRAO Director Fred Lo and Assistant Director Dale Frail, an ad hoc committee was convened to discuss the optimal response of NRAO to the impact of the G2 cloud with the Sgr A* accretion region (Gillessen et al. 2012). The committee held a two-hour telecon on 8 June 2012 and then produced this brief report.

The committee was unanimous in their enthusiasm for the opportunity that the encounter provides for probing the astrophysics of a unique and important astrophysical source. Theoretical estimates point to a good chance of detecting radio emission from the bow shock of G2 as it plows through the ambient hot medium near the pericenter. A change in the radio/mm polarization is expected to accompany the initial encounter and may provide an early estimate of the increase in the mass accretion rate in the outer flow. Within a few year timescale, an increase in the radio flux from the inner accretion flow is expected to occur, accompanied by a resolvable change in the size of the radio emitting region. We emphasize, however, that given the uniqueness of this event, there could be other effects and outcomes that have not been thought of and that the community should be prepared for. For all these reasons, we recommend regular and frequent flux monitoring over a wide range of frequencies. We recommend observations prior to the pericentric passage to establish a firm baseline and continued observations through and after the pericentric passage of G2. A host of other observations are viewed as compelling if the source enters into a state with significantly higher flux density and/or accretion rate.

Specific recommendations to NRAO are:

- Weekly VLA monitoring of flux density beginning January 2013 and continuing for at least one year. Monitoring should cover as much of the spectrum as possible from 1 to 50 GHz. Lower frequencies will be more sensitive to early bow shock emission, while higher frequencies will be more sensitive to increased accretion rate at the black hole. These observations should be carried out as service observing by NRAO. We note that total time required for these observations for sensitive detections and appropriate calibration is very short ($\sim$ minutes); the lower limit to the time is primarily set by slew time and scheduling granularity.

- Weekly ALMA monitoring of flux density over the same time period in bands 3, 6 and 7. Ideally, these would be carried out as service observing, as well, but we recognize that this may not be feasible. Similar time requirements as for the VLA are required for ALMA.
- Both VLA and ALMA data should be automatically processed and the results distributed to the community as quickly as possible.
- ALMA polarimetry for a point source should be commissioned in advance of periastron. The ALMA flux monitoring should include polarimetric measurements, if possible. These observations will be sensitive to changes in the rotation measure due to increased mass density at large radii.
- NRAO should establish a committee consisting of community members and NRAO staff to oversee monitoring results and advise on DDT proposals and suitability of follow-up based on radio, millimeter, and multiwavelength data.
- A trigger criterion should be set to establish a new observing mode. A suitable trigger is a factor of 3 increase of flux density over the historical average at any frequency; past monitoring has shown that such flares are extremely rare. We recommend that the aforementioned DDT committee should evaluate trigger thresholds in more detail.
- In the event of a trigger, we proposed a list of follow-up activities: more intensive flux monitoring, and astrometric VLBA imaging.
- Other users may have good ideas for follow-up: We encourage ToO submissions through the regular NRAO processes. We recommend that proposals received on August 1 and February 1 be on equal footing for scheduling purposes.

In §2, we summarize the case for expected increases in radio/millimeter flux density. In §3, we discuss the power of ALMA polarimetry to probe the accretion process on a range of scales. In §4, we discuss the value of imaging observations with VLA and VLBA following detection of increased radio/millimeter activity. And in §5, we give some of the context of planned multi-wavelength observations that may also serve as triggers of intensive radio monitoring.

2. Expectations for Radio/Millimeter Emission from the G2 Encounter

The accretion flow around the supermassive black hole at the center of the Galaxy, Sgr A*, produces $\sim$ 1Jy of quiescent radio flux at frequencies $>$ 1 GHz. This emission originates from the innermost $\sim$ tens of Schwarzschild radii (R_S) of the accretion flow and/or jet, owing to synchrotron radiation from relativistic electrons. Additional radio emission is expected from the encounter of the ionized gas cloud G2 with the Galactic Center region; however, there is some uncertainty in the properties and the timescale of this emission as discussed below.

2.1. Bow Shock Emission

The pericentric distance of G2 is estimated to be 4×10^{15} cm, which corresponds to 3100 R_S given the mass of the supermassive black hole. At this distance, the electrons in the accretion flow are hot but not relativistic, and, therefore, would not produce an observable amount of radio emission in the initial stages of the encounter. However, the velocity of the gas cloud at the pericenter will be 5400 km s^{-1}, which is approximately two times the sound speed of the gas at this distance from the black hole. Moving with a Mach number of $\mathcal{M} \approx 2$ near the pericenter, the cloud is expected to produce a bow shock, which can easily accelerate electrons into a power-law distribution in Lorentz factor γ_e.

The magnetic field strength, density, pressure, and the temperature of the shocked gas can be estimated using standard shock conditions, and yields the expected mean energy of the electrons to be close to $m_e c^2$. For a cross-sectional area of π (10^{15} cm)^2 for the bow shock and an expected encounter duration of $\sim$ 6 months, the total number of non-thermal electrons in the shock region is estimated to be $\approx 10^{50}$. The power-law index p of the electron distribution has some uncertainty but particle-in-cell simulations show that a large fraction of shocked electrons form a tail with $p = 3 - 4$ (see, e.g., Riquelme & Spitkovsky 2011). Given that a power-law index of $p = 2.5$ is observed in relativistic shocks, we may consider $p = 2.5 - 3.5$ as a possible range for the electrons in the G2 bow shock.

For $p = 3.5$, the expected additional emission from Sgr A* at $\nu = 1$ GHz is 0.6 Jy, while for $p = 2.5$, the additional emission at the same frequency will be approximately 40 Jy, which points to a fairly reasonable chance of detectable synchrotron emission at GHz frequencies from the bow shock of G2 around the pericenter passage in mid-to-late 2013.

2.2. Emission from Increased Mass Accretion at the Black Hole

There is no generally accepted model for the emission of Sgr A*. The radio emission has been explained with either emission associated with the accretion flow directly or with a plasma outflow (jet). Nonetheless, in either case the level of radio emission is directly related to the rate with which matter flows towards the supermassive black hole. Hence, an increase in the accretion rate, $\dot{M}$, due to the interaction of Sgr A* with the cloud G2 should be reflected in the Sgr A* radio flux.

The net increase in the mass accretion rate in the inner tens of Schwarzschild radii is uncertain due to uncertainties in the gas capture rate and the mass loss within the accretion flow, but is estimated to be in the $10^{-8} - 10^{-4} M_{\odot}$ yr^{-1} range, which is a factor of a few to as much as a few orders of magnitude above the current mass accretion rate. When this enhancement reaches the central region over a few years, it is very likely to cause a significant increase in the radio luminosity as well as in the size of the radio emitting region (see, e.g., Moscibrodzka et al. 2012; arXiv 1204.1371). Within any model of radio emission from Sgr A*, the flux enhancement at this stage may be a factor of a few or more above the current level and be detectable with high significance. Finally, if the density enhancement remains clumpy as it makes its way to the inner accretion flow, quasiperiodicity and flare-like signatures may be present in the emission above a GHz.

The main question then is: what is the expected increase in accretion rate and on which time scale. While the actual response to changes of the accretion rate within a few Rs will be almost instantaneously, i.e., within hours, the free-fall time scale for material to reach the event horizon from about 3000 R_S is a few months. Viscous time scales can be one to two orders of magnitude slower, however. However, some of the currently favored radiatively inefficient accretion flow models can indeed have processes operating close to free-fall speeds or some fraction thereof. As an example, given an infall velocity at 10% of the free fall-speed one would expect the radio flux from the inner flow to increase $\sim$ 2 years after the main impact.

In both jet and accretion flow models, the radio flux density is a strong function of the accretion rate, following laws of $\dot{M}^{1.4}$ and $\dot{M}^{2}$, respectively. Hence the flux increase could be anywhere from a few percent, in the most pessimistic case, to many orders of magnitude for most of the parameter range. Such a huge increase in flux would also have dramatic consequences on the visible size of Sgr A* making it well resolvable with the VLBA or the VLA. A radio jet, for example, would become clearly visible. Such an event would therefore allow one for the first time to see the onset of (low-luminosity) AGN activity in a supermassive black hole with unprecedented detail.

Hence, it will be important to do a regular flux monitoring of Sgr A* with the VLA as well as ALMA in polarization mode, starting with weekly intervals within the first year from periastron passage. The frequency can then be reduced to monthly monitoring in subsequent years. The best frequency for the VLA is 43-22 GHz, since the higher resolution allows one to observe Sgr A* also in compact array configurations. Moreover, the emission comes from closest to the black hole. For ALMA, bands 3,6, & 7 are most ideally suited as this is where the Faraday rotation is best seen.

3. ALMA Polarimetry as a Probe of the Large Scale Density and Accretion Process

The millimeter and submillimeter polarization of Sgr A* should be a leading indicator of the impact of G2 onto the accreting material around the black hole. More than a decade of linear polarization observations have shown that Sgr A* has a large and stable Faraday rotation measure (RM). The RM, the integral of the density and line of sight magnetic field component through the accretion flow, is presumed to arise primarily from material at hundreds to thousands of Schwarzschild radii. The projected pericenter distance for G2 will place it directly into this part of the accretion flow, and rather than waiting for material to accrete to the inner flow, we can expect that density and magnetic field disturbances caused by the approach and impact of G2 should be perceptible through the RM. This makes millimeter polarimetry one of the most important monitoring activities that can be undertaken before and during the passage.

Our knowledge of the RM suggests that is will be an excellent diagnostic of the cloud impact. Despite careful studies, there is no evidence of changes in the RM over more than 10 years. Since initial linear polarization detections in 1999 the RM has had a persistent sign, which suggests significant order in the magnetic field at the radii where it arises. Furthermore, the absence of clear variations in the magnitude of the RM at the 20% level indicate some constancy in the accretion rate there. Accordingly, changes in the RM observed over the coming years can be assumed to be related to the cloud impact. From our knowledge of the orbit and the timing of these changes, we can expect to learn a great deal about the density profile in the accretion flow and the radius providing the dominant contribution to the RM.

Sgr A* is also intrinsically linearly and circularly polarized. The linear polarization is highly variable, changing in degree and direction on hour timescales though processes that are believed to be governed by the inner accretion physics. As cloud material accretes inward, changes in the intrinsic linear polarization behavior will likely follow, though this may become difficult to observe because of depolarization if the RM increases significantly. Like the RM, the circular polarization is stable, it has not changed sign over 30 years at centimeter wavelengths and is observable to at least 350 GHz. The timing of any perturbation from G2 may also help explain the origin of the circular polarization.

ALMA will be key to fully exploiting the opportunity afforded by the arrival of G2. Polarimetric monitoring with ALMA should be undertaken in band 6, possibly in combination with band 7. At band 3 the linear polarization is intermittent, while at bands 7 and 9 the difference polarization position angle between sidebands ($<$ 1deg) will be hard to measure reliably. Short observations in which cross-polarized correlations (not available in cycle 1) are recorded should be adequate to determine the difference in polarization direction between sidebands, and thus the RM, if some additional commissioning work can be undertaken to characterize the instrumental polarization terms.

4. Astrometric Imaging Follow-Up with the VLBA and VLA

If Sgr A* goes into an outburst owing to rapid accretion of material toward the black hole, the following questions could be addressed by astrometric imaging observations with the VLBA (and possibly the VLA).

1) Is the accretion onto a disk, resulting in jet emission, or is the accretion quasi-spherical?

2) Assuming jet emission, is the peak brightness progressively more offset from the black hole at longer wavelengths (ie, "core-shift")?

3) How does the emission evolve over time (optical depth as a function of observing frequency and time)?

These questions are fundamental to understanding the physics of jet emission from AGN and it is possible that Sgr A* could provide "Rosetta Stone" information, owing to its proximity and our knowledge of the accreting gas.

In order to prepare for such observations, it would be important to have a "control observation" of Sgr A*, shortly before any accretion event. This would require astrometric VLBA observations at 22 and 43 GHz relative to background quasars (similar to those reported in Reid & Brunthaler 2004) in order to re-determine the angular separations with high accuracy (0.05 mas) and to avoid less accurate extrapolations based on older positions/proper motions.

After an outburst, continued VLBA astrometric imaging at intervals spaced by (1,2,4,8...) days would be advisable, given that AGN jet pattern speeds have been observed between 0.1 and 10c.

If the jet expands at speeds of order the speed of light, VLA observations (with resolution 0.1") starting about 5 days after outburst might be able to resolve the emission.

5. Multi-Wavelength Observations

We will have a unique opportunity to study near-IR (Near-IR), X-ray, γ-ray (GeV and TeV), radio and submm flare emission arising from accretion onto Sgr A* due to a dust cloud that is on a path to reach Sgr A* in the summer of 2013. Past observations have indicated that radio flare emission from Sgr A* lags behind peak flare emission at near-IR, submm and X-ray wavelengths. However, the exact amount of time delay has been uncertain given that we have never identified a powerful flare that could be followed in the time domain simultaneously at different wavelengths. Thus, monitoring of the flux of Sgr A* at multiple wavelengths to identify a strong flare could be a powerful probe of the emission mechanism as the G2 cloud accretes over its dynamical time scale of $\sim$6 months.

Radio and X-ray flare emission are the key carriers of information that signal the onset of an accretion event and radio observations that we recommend will be used to trigger follow-up multiwavelength observations in X-rays, near-IR, submm and γ-rays. There are currently three programs that have been approved and/or committed to monitor the flux of Sgr A* at near-IR with the VLT, at γ-rays with *Fermi* and at X-rays with SWIFT. Several nights of near-IR observations of Sgr A* will be scheduled with the VLT as the G2 cloud gets closer to Sgr A* between March and July 2013. A proposal has been approved for pointed observations of *Fermi* LAT toward Sgr A* for two years, to be triggered by either the detection of γ-ray flare activity or by an enhanced duty cycle for X-ray flaring, indicating the onset of an accretion event. In addition, the G2 cloud encounter was included in the SWIFT senior review and Swift monitoring observations of Sgr A* has been committed by the director Neil Gehrels. There are also proposals requesting time to monitor Sgr A* with XMM and Chandra as these proposals are currently being reviewed. Chandra may schedule observations up to a maxiumm of 300ks if current proposals are accepted. ToO and DDT are also available if Sgr A* is showing a sign of activity.

Fermi observations have detected a bright γ-ray source coincident with Sgr A*. Given the low spatial resolution of *Fermi* data, radio observations could be useful to identify the source of flare emission arising from Sgr A*. Given the high duty cycle of radio flare emission, the detection of bright flares at radio wavelengths using the VLA will be most useful to trigger pointed observations in X-ray (SWIFT, Chandra, XMM), submm (ALMA, SMA, CARMA), γ-rays (*Fermi* and HESS).