Workshop Summary: Formation and Evolution of Stars Near the Galactic Center

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A. Ghez: *Observations of Stars Near the Galactic Center*

- Contents of Galactic center on < 10 pc scale:
  - Mini-spiral inflowing stream of gas
  - $M=10^4 M_\odot$, R=1.5 pc circumnuclear disk; gas cavity around Sgr A* source
  - Sgr A* cluster of stars within 1” -> 0.04 pc
- Observations of Sgr A* cluster stars from IR AO imaging:
  - Proper motions of 200 stars tracked with Keck since <1998;
    first plane-of-sky velocities, then accelerations, then full orbits (~10)
  - 32 objects tracked within 1” of Sgr A*
  - Especially interesting stars: SO-2 (orbital period 15 yrs);
    SO-6 (highly eccentric orbit); SO-16 (periapse 80 AU from Sgr A*)
  - Based on independent orbit solutions, $M_{BH} = 3.7 \times 10^6 M_\odot (R_0/8\mathrm{kpc})^3$
    $v_{BH} = 30 \pm 30$ km/s
  - Eccentricities are consistent with isotropic distribution (but observational bias toward eccentric orbits)
- Spectroscopic observations of Sgr A* cluster stars stars:
  - Absence of CO absorption lines => young stars
  - For stars in close approach to Sgr A*, Br □lines shifted by 1100-1500 km/s => can separate from local gas emission => consistent with OB star atmospheres

Ghez, cont.

- "Paradox of youth" :

--How did such apparently young stars come to be found in an environment where SF is so difficult?

--Same, but more extreme version of question for He I emission-line stars at 0.1 -0.5 pc from ctr.

--Would need n > 10^{14} cm^{-3} at R=0.01 pc; n> 10^{8} cm^{-3} at R=0.1 pc to form in situ given strong tidal gravity

--> larger than any observed gas densities

- Possible solutions include:
  - ❧ Tidal heating of atmosphere upon closest approach to BH (*is thermal time long enough for atmosphere not to show variations?)*
  - ❧ Stars are actually stripped giants
  - ❧ Stars are accreting compact objects
  - ❧ Stars are merger products
  - ❧ Stars formed as bound clusters at larger distance (cf. Arches, Quintuplet at R~ 30 pc), migrated inward via dynamical friction

R. Genzel: *Dynamics and Evolution of Nuclear Star Clusters*

- Observing galactic center stars with NAOS/CONICA and SPIFFI on the VLT
- Data sets:
  - $10^{3.7}$ stars observed
  - 10^{3} proper motions obtained
  - $10^{2.5}$ spectra and radial velocities
  - 10^{2} stars with los v + proper motions
  - 10^{1} stars with full orbits I Sgr A* cluster
- Central stellar distribution:
  - Surface density from counts of faint stars peaks directly at Sgr A* position
  - Central density $□_* = 3.7 \times 10^7 M_\odot (R/0.04\ pc)^{-1.4}$ in inner region; R^{-2} further out
  - Total mass ~ $10^4 M_\odot$ in central cusp; sufficient density for stellar collisions
- Stellar populations:
  - From K luminosity fnct, *nuclear cluster* is either old metal-rich + young burst
    or constant SF rate pop
  - Central cusp lacks HB stars
  - Spectra are similar to massive stars in Arches, Quintuplet
  - Star formation rate appears to have peak ~ 10^{7} yrs ago

Genzel, *cont.*

- Dynamics of stellar components:
  - Proper motions =>

    late-type stars consistent with isotropic distribution

    early-type stars preferentially (counter-) rotating in two inclined planes

    IRS 16 probably not a bound cluster; apparent clustering from inclined disk

    --- Evidence that young stars migrated inwards as clusters and then dispersed

M. Reid: *Is Sgr A* a SMBH at the dynamic center of the Milky Way?*

- Is Sgr A* at the center of the stellar cluster?

  -- yes, within 10 mas (orbit of S-2 has pericenter only 15 mas from Sgr A*)

- Is Sgr A* tied to the stellar cluster?

  -- yes; comparing proper motions from IR, radio; velocity with 70 km/s

- Is Sgr A* at the dynamic center of the Milky Way?

  -- yes, based on apparent motion of Sgr A* wrt background QSOs:

  - apparent motion is *almost* along IAU galactic plane
  - Sun's apparent galactic angular velocity is 29 km/s/kpc (compared to 27.3 from Hipparcos)

- Does Sgr A* have peculiar motions wrt the galactic ctr?

  -- No; taking v_z =7km/s for Sun (Dehnen & Binney), Sgr A* v_z=0.8±0.9 km/s

- Does Sgr A* contain all the mass in central ~ few 100 AU?

  - Yes, within 60%: $M_{lim} \sim GM(R)m/(RV^2)$; V< 2 km/s => M> 2 × $10^6 M_\odot$

    M= 3 × $10^6 M_\odot$ from S-2's orbit, within 0.001 pc

- Could exotic dark matter dominate the Galactic center's mass?

  - No; less than 40% of the gravitational mass, based on radio proper motion,

    M= 2 × $10^6 M_\odot$ within 1 AU

A. Goodman: *Overview of Star Formation in the Galaxy*

- How fast is star formation?
  - Lifetimes of different stages of YSOs: log(t/yr)=4,5,6,7 for Class O, I, II, III based on relative populations;
  - *how fast do cores form/collapse? (relative populations of cores with vs. without embedded stars)*
  - *how fast do clouds form/evolve? (from correlation with spiral arms; stellar clusters)*
  - *Does fast=dynamic? (e.g. condensation from turbulent vs. gravitational compression)*
- How does the IMF vary with environment?
  - Taurus (nearby dark cloud with weak turbulence) has flattish IMF
  - IC 348 (stellar cluster in GMC with strong turbulence) has increase toward low mass; peak at few $\times$ 0.1 $M_{\odot}$
  - Internal velocity dispersions systematically increase with size in main-disk clouds
- Lessons from PV Ceph:
  - Deceleration of knots in outflows => D/V tends to overestimate age
  - Relative positions of knots suggest very high velocity (20 km/s)

    --- possible ejection from neighboring cloud

    --- where did core surrounding star come from?
- Implication of general lack of high-velocity stars for star formation mechanisms

  initial conditions and their effects; *do transient dense clusters really exist?*

M. Morris: *Idiosyncrasies of Star Formation Near the Galactic Center*

- Factors in the initial conditions within ~ 150 pc of GC that may affect SF; IMF
  - Gas surface density $\Sigma \sim 1000\ M_\odot/pc^2$ (100 × outer galaxy),
    velocity dispersion $\sigma_v \sim 15$ km/s (2 × outer galaxy) (*inter- or intra-cloud?*)

    ⇒ *self-gravitating clouds should form more rapidly and be less massive:*

    $t_J \sim \sigma_v / G\Sigma$ (0.02 × outer galaxy); $M_J \sim \sigma_v^4/(G^2\Sigma)$ (0.16 × outer galaxy)
  - Magnetic fields *B*~mG (100 × outer galaxy) (*ambient or within clouds?*)

    ⇒ mass-to-flux for largest clouds (~□□/B_{amb}) similar to outer galaxy (marginally critical)
  - Temperature in molecular gas T~50-70 K (2-7 × outer galaxy)

    Effects for compressibility/minimum scale of overdense perturbations in cloud? (cf.σ_v)
- Circumnuclear disk: clumps possibly up to $n=10^6-10^8$ cm^{-3}
- IMF
  - Mass segregation evident in Arches cluster (age 2.5 10^6 yrs); flatter MF than Salpeter?

    Many high mass stars are present; is there evidence for different turnover in MF?
- Dynamical friction to carry star clusters into central pc
  - Need $M>10^6\ M_\odot$ cluster for short enough timescale with drag against stars
  - Issues: too many evaporated young stars> 1pc; too many surviving young stars; IMBH helps
  - *Could drag against gas disk help with limits? (cf. Ostriker 1999; Goldreich& Tremaine)*

    $F_{DF}(gas) / F_{DF}(stars) \sim (\square_{gas}/\square_*)(\square_*/\square_{gas})/\ln\square_* \sim 100(M_{gas}/M_*)/\ln\square_*$

V. Bromm: *Simulating Star Formation Through Cosmic Time*

- Population III:
  - No B-fields, no metals, initial conditions from CDM
  - Were first stars very massive? -- may be necessary for early reionization (WMAP)
  - Evolution from simulation: condense out clouds at T~ 200 K (H_2 cooling), $n \sim 10^3$-10^4 cm^{-3} (critical density) => $M_J \sim 10^3\ M_\odot$

  what sets the total efficiency of gas -> Pop III star conversion in these halos?
- Transition to Population II:
  - critical metallicity $Z=10^{-4}$ for "normal" interstellar coolants (C^+)
  - Supernova explosions drive metals out of low-mass halos into IGM
- Present-day star formation:
  - simulation of 50 $M_\odot$ cluster formation; initial T=10K, R=0.4pc; supersonic turbulence
  - No magnetic fields
  - Result: formation of mix of stellar and BD-mass objects
  - Total SF efficiency is ~ 40%
  - Close encounters kick stars out at up to 5 km/s

    Is SF efficiency too high? Are runaways so common? (initial density in phase space may be too large => cluster too compact)

F. Shu: *The Stellar IMF*

- Mass-to-flux
  - M/□ = □/B; critical value is 1/(2□ G $^{1/2}$)
  - Typical apparent ratio ~ 3× critical, but □ overestimated, B underestimated from projection

  $□_{ISM}/B_{gal}$ ~ critical in Galactic disk; dynamo needs to make $\langle v_A \rangle \sim c_s$ but how does it know about SF? Are B-fields necessary to make GMCs if Q is not <1? (YES)

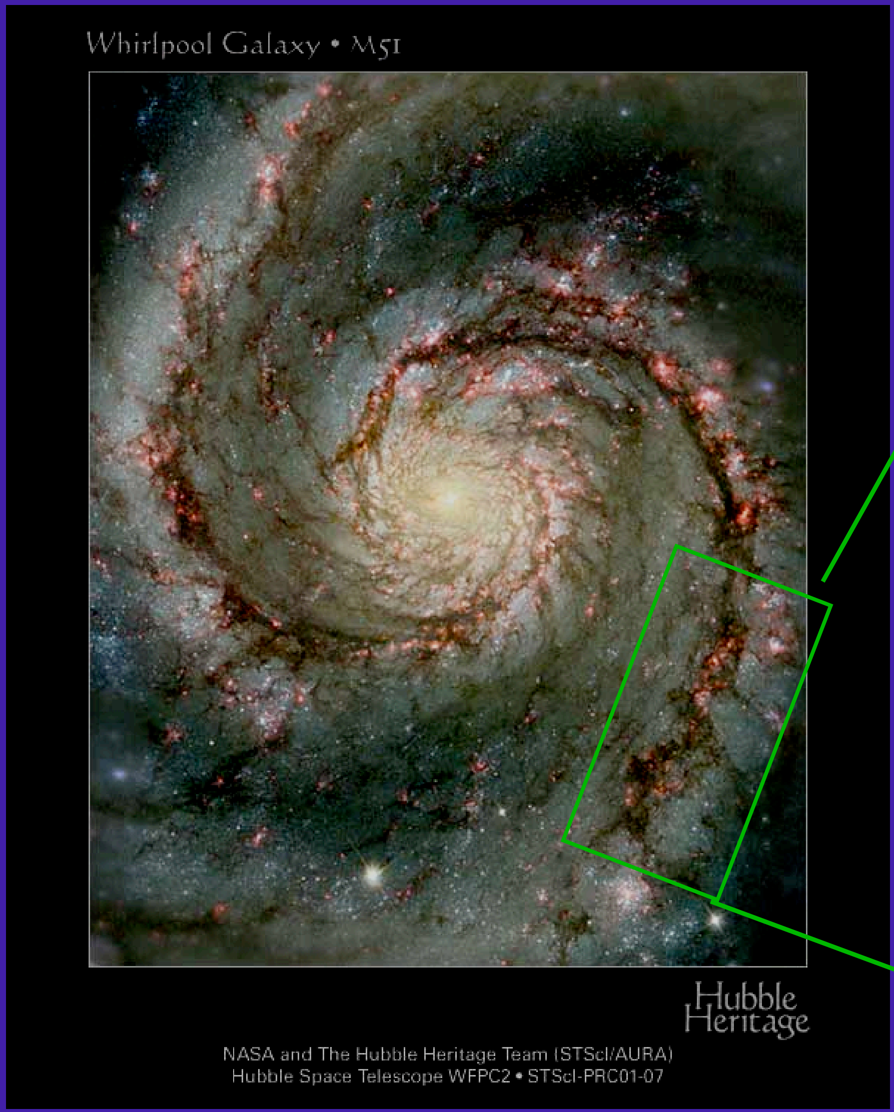
A "false theory" of star formation:

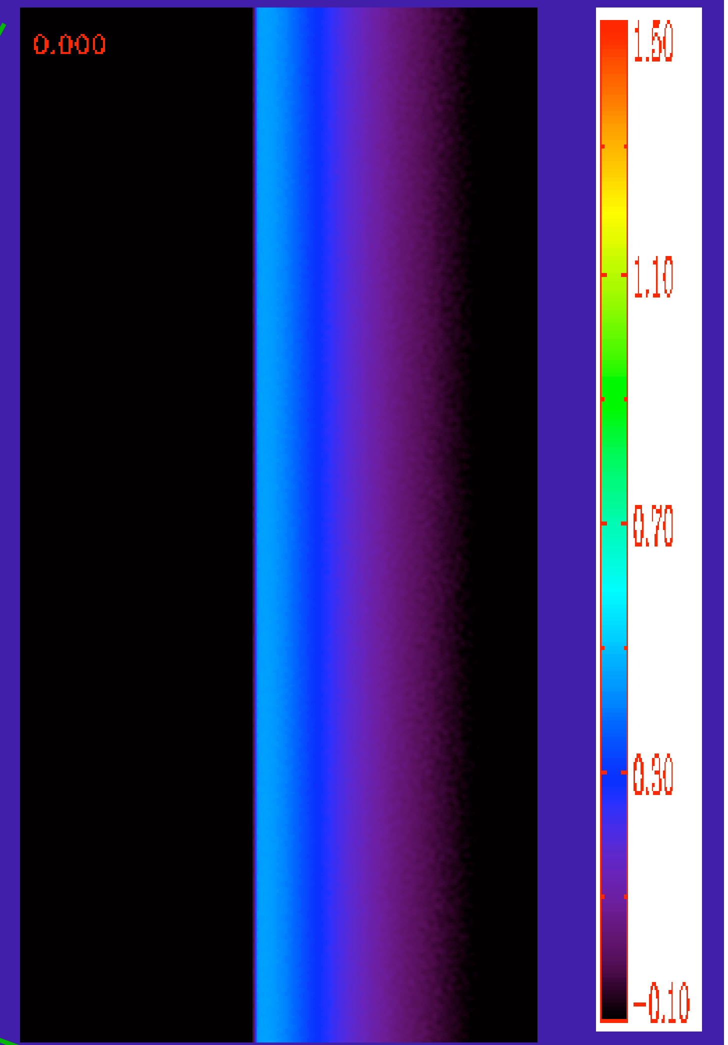
- For supercritical collapsed core + subcritical magnetically-supported envelope, geometric mean of mass-to-flux ~ critical ; stellar mass is dimensionless constant × core mass
- Problems: this requires 10^7 on stellar surface! And any rotation would □ catastrophic magnetic braking of disk
- Solution: ambipolar diffusion (assisted by turbulence in cloud or disk)

What defines core masses => stellar masses?

- Jeans-mass core has M~ L_J^2 □ with L_J =($□_v^2$ + c_s^2)/(G □) if thermally+turbulently supported;
  magnetically critical □ 1/□~ 2□ G $^{1/2}$/B ; combine to obtain $M_{crit,turb}$ ~ $□_v^4$ /(G $^{3/2}$ B)
- For IMF, need total mass at each velocity and relation between v and B;
  mass(v) distribution from swept-up outflows with B v yields Salpeter-like IMF slope,
  dN/dM $M^{-2.35}$
- Final IMF needs shift in log(M) for each bin due to wind mass losses; suppression at high-mass end from radiation pressure

Cloud formation in magnetized spiral arm



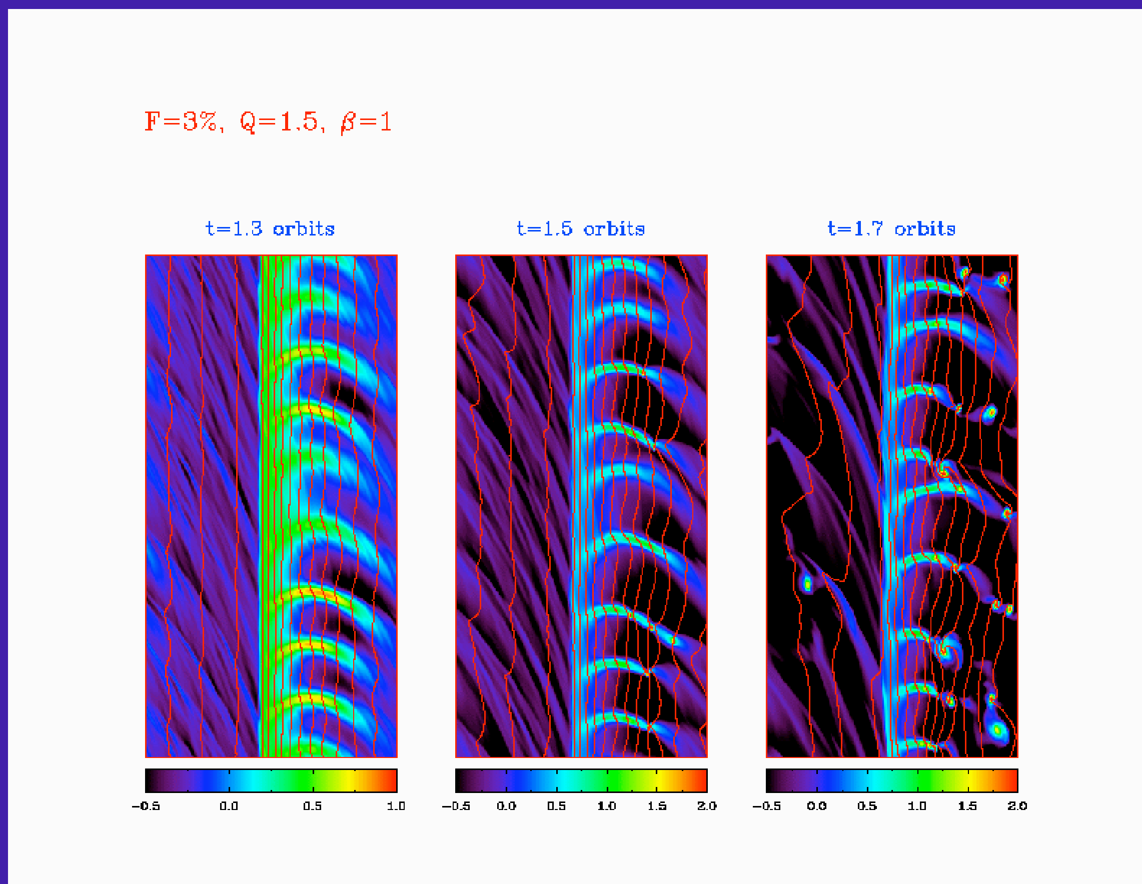


log

Q_0=1.5, v_A/c_s=1, F=3%

Spiral arm MJI: formation and fragmentation of spurs

- Local reduced/reversed shear profile: dln □ / d ln R= □/$□_0$ - 2
- MJI develops in dense region and is convected downstream out of arm; interarm shear creates “spur” shape; fragmentation follows
- Fragment mass □ Jeans mass at spiral arm peak □ few × $10^6 M_\odot$



L.Hartmann: *Dynamic Star Formation*

- From ages of associations in clouds, infer rapid onset of SF (<1Myr) after MC formation and rapid dispersal of cloud after SF (<5 Myr)
- Sco OB2: externally-driven sweep-up of gas into cloud (t_{cross} ~100 Myr, ages <15 Myr)
- Can molecular material appear so quickly? -- from 15 km/s shock, with n=3 cm^{-3}, takes 10Myr to reach A_v=1 and build up CO , but H_2 may be present at lower A_v
- Taurus: paradigm of low-mass star formation
  - Turbulence not internally-driven since structure is dominated by large-scale filaments -- swept up

    [but see movie -- gravity can produce filaments too]
  - Filaments have internal core PA aligned with filament directions
  - Stars are correlated with filaments; ages ~ Myr velocity dispersions should be < 0.4 km/s

    Do stellar velocity differences obey Larson's Law?
- Is the IMF environment-dependent?
  - Taurus (more quiescent, less dense cloud) has fewer low-mass stars than IC348

    What sets lower-mass cutoff in IMF? Is initial smallest supersonic scale important?

Collapse of a turbulent, magnetized cloud

Simulation of evolution in magnetically supercritical self-gravitating cloud (Ostriker, Stone,& Gammie 2001)

T. Alexander: *Orbital capture of stars by SMBH; tidal effects on stars*

- How to collect massive MS stars: capture with dense cusp of stellar BHs
  - From mass segregation, # of smbh approaches # of MS within 0.01 -0.1 pc
  - Young star that forms far away is deflected onto orbit crossing through center; is captured in 3 body interaction involving smbh and SMBH
  - For each passage, require P(capture) ~ 10^{-7} in order to maintain observed OB star population
  - Would this imply too many field OB stars within slightly larger volume?
- Orbital properties:
  - minimal apoapse is ~0.01pc due to disruption b SMBH
  - Distribution of eccentricities can probe SMBH mass
- Tidal effects on stars: a few % of stars have survived a close encounter with SMBH; been tidally heated
  - Star with smallest apoapse is the brightest in the sample

J. Goodman: *Massive star formation in accretion disks*

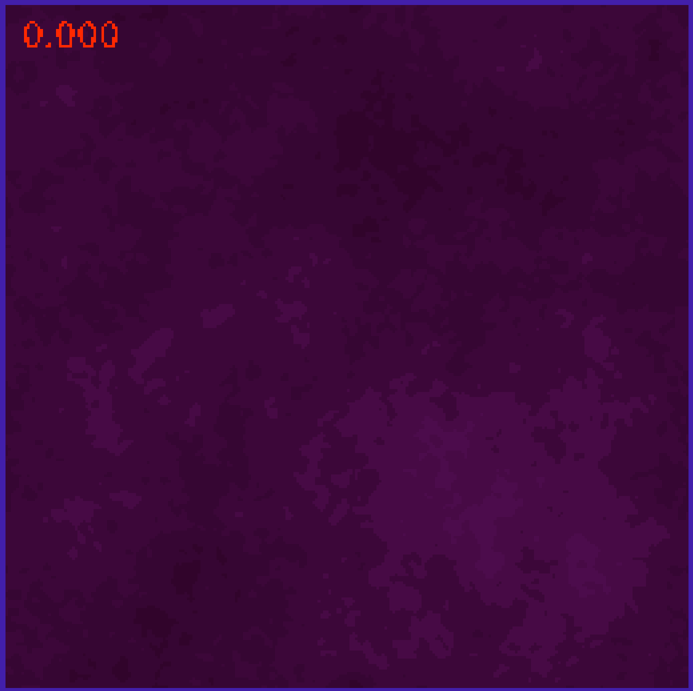
- *The problem of GC SF: It's not that the tidal force is too large…. it's that the density is too low!*
  - Binary stars deal with this problem by forming out of an accretion disk
  - Should eccentricities be small for objects formed in a disk? Not if the mass ratio of the two largest bodies is not too small
- Accretion rates and self-gravity
  - Toomre $Q = c_s □ /(□ G □)$ -> $M_{BH}/(2 □ R^3 □)$ for Q>1 , or $[M_{BH}/(2 □ R^3 □)]^{1/2}$ for Q<1
  - $Q = 3 □ c_s^3 /(G \; dM/dt)$
    - "ISM accretion disk" (optically thin) : c_s =10 km/s , □=0.01, and Q=1 => 0.007 $M_\odot$/yr
    - Optically thick accretion at Eddington rate => outer disk always has Q<1
    - Initial mass that forms is $M_{Toomre} \sim □ (H/R)^3 M_{BH}$
    - □ Mass can grow further until it reaches isolation mass ~ $(M_T \, M_{BH})^{1/2}$ corresponding to $10^3 \, M_\odot$ for Galactic center
    - Also would have inward accretion with the disk

Gravitational instability in shearing disk

Kim & Ostriker (2001a)

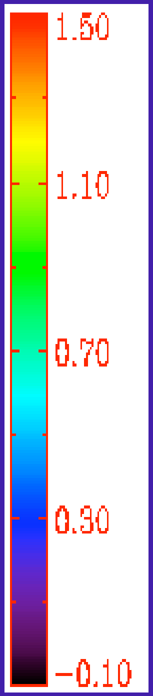
unstable

t/t_{orb}



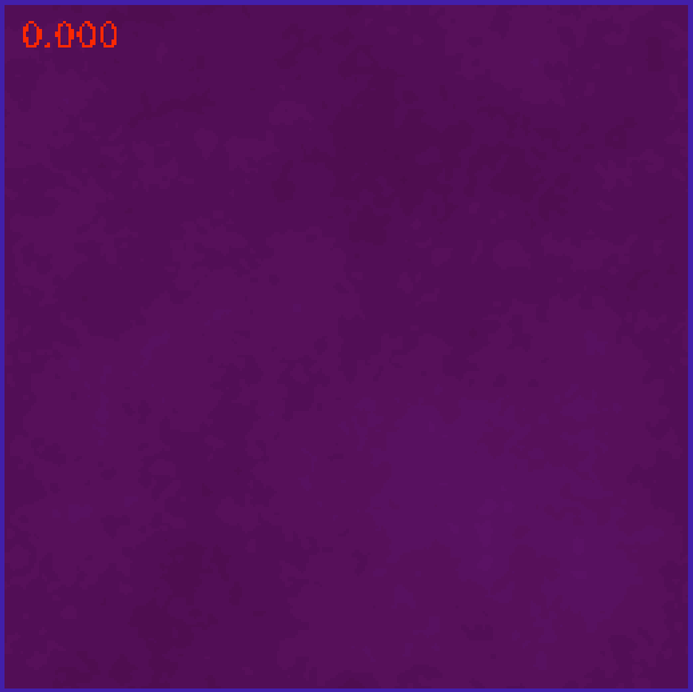
v_A/c_s=0.3, Q=1.0

log



stable

t/t_{orb}



v_A/c_s=0.3, Q=1.5

C.Clarke: *Star-Disk Interactions in Galactic Nuclei*

- Stars passing through a disk change their orbits:
  - $V >> c_s$ => strong shock; crossection = physical area
  - Many passages through disk needed for significant change in orbit
  - Even if $\square_{disk}$ is maximal (function of T, R, M_{BH}), star will only become bound if within 100 AU
  - For captured stars, circularization timescale is shorter than inclination damping
  - Disk loses mass (slowly) be repeated perforations

Observable consequences:

Shock would produce 10^8 K gas; if optically thin, seen as Bremss; if thick seen mostly as reprocessed IR

Is there a disk in GC, anyhow?

constancy of S2 in K band => disk either optically thin at K or large inner hole

L band excess possibly interpreted as reprocessing from disk

Overall conclusion: no current cold disk is present

B. Hansen: ***Is there a second BH in the GC?***

- Fix the problem of slow migration by increasing mass: star cluster
- Fix the problem of tidal disruption before reaching center by high central density
- Fix the problem of core collapse/evaporation by putting a massive object in cluster
  - Massive object (10^3-10^4 $M_\odot$) could have formed by physical collisions/runaway merger if segregation time < main sequence lifetime (would it collapse to IMBH?)
- DF only works to bring MS+ IMBH cluster to radius where $\rho_* \sim M_{BH}/ R^3$;

  stalls at ~ 0.01 pc (*gas would be better, if present!)*

Where do stellar eccentricities come from? -- analogous situation to

Sun, Saturn, comets -> Oort cloud

IMBH may also be useful for ejecting excess other stars in central pc

Observable?

proper motion of Sgr A* from orbital reflex -- possibly observable with VLBA?

gravitational wave source for LISA

X-ray source?

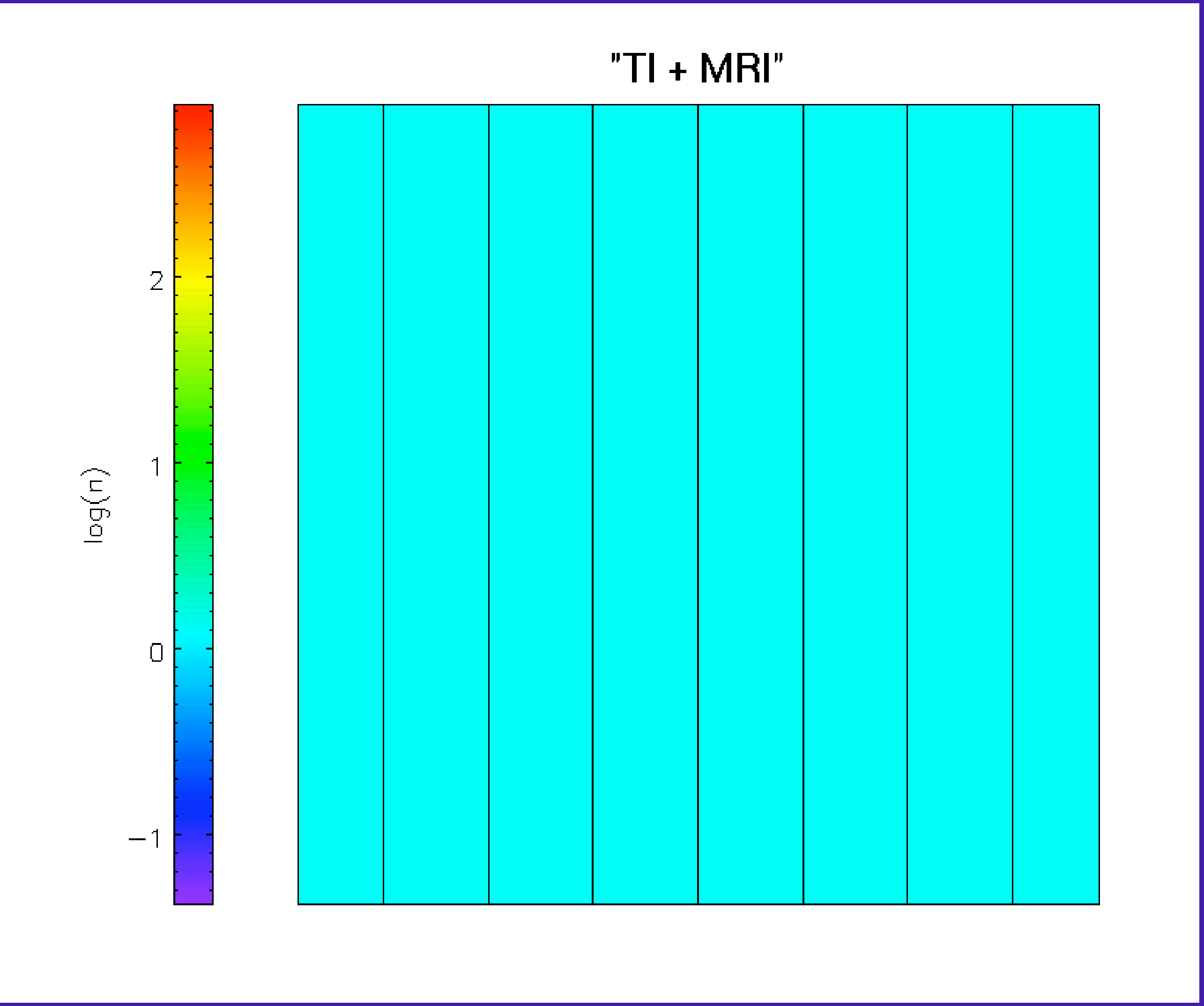
J. Grindlay: *Stellar remnants in the GC*

◆ ChamPlane survey (Chandra ACIS-I)

to assess accretion source population of galaxy (CV's, quiescent LMXB's, BH accreting from ISM)

- Log N vs log S => largest excess X-ray point sources is in Galactic bulge
- 300 faint Chandra sources with distribution consistent with extension of 1/□ central cusp
- Also have "general bulge" distribution
- 7 hard-spectrum cusp sources possibly HMXBs
- Deep IR imaging is needed for identification of cusp sources

MRI in multiphase medium: ISM accretion



Thermal instability followed by MRI development in two-phase disk

(Piontek & Ostriker 2003)

Star formation *near* the Galactic center…

- gravitational instability develops more rapidly under weak-shear conditions (in bulge) than for strong shear conditions (outer-disk V_c=const) for given Σ_{gas}
- t_{grav} Σ_{gas}^{-1} may be shorter than stellar evolution time => more efficient star formation

…no problem!

Kim & Ostriker 2001a

Some questions for the future about star formation in the Galactic Center…

- For observation:
- Stars form from molecular clouds; what are the detailed properties of the GC clouds?
  - mass spectrum
  - Is thermal pressure confinement significant?
  - are they all self-gravitating? top-down or bottom-up formation?
  - do they obey Larson's Law's?
  - Evidence of subclumping from molecular excitations?
- Is there evidence of differing MF compared with outer Galaxy SF (esp low end turnover)? differing SF efficiency?
- For theory and simulation:
  - How should/does mass spectrum of clumps, cores, stars depend on dimensionless parameters (M/M_J, c_s/v_A, v/c_s)?
  - Are there aspects of GC conditions that would bias the IMF toward predominantly high masses?
  - What determines the star formation efficiency?
  - Given an "ISM accretion disk" feeding gas in at ~0.005-0.05 $M_\odot$ /yr, what sort of disk could develop in the GC, and could it provide significant DF for clusters?