S-Stars in the Galactic Center

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1 Observations and Basic Picture

1.1 The Sgr A* Cluster, or the "S-Stars"

1. Within $1''$ ($r < 0.04$ pc) of the Galactic Center
2. 17 stars with measured proper motions ($14.0 < K < 16.8$)
3. The stars in this cluster appear to be normal main sequence B-stars from spectroscopic observations given information on spectral type and rotational velocity.
4. Masses range from $\sim 3M_\odot$ to $\sim 15M_\odot$ and lifespans of $\sim 10^7$ y to $\sim 10^8$ y. (A typical star is a B2 main sequence star with $M \sim 10M_\odot$, $R \sim 4.5R_\odot$, and a lifespan $\sim 2 \times 10^7$ y
5. The orbits of the S-stars appear to be isotropically distributed.
6. There appears to be a deificit of red giants in this region.

1.2 Stars within the Central Parsec

1. In the region 0.04 pc $< r <$ 0.4 pc, the stellar spatial distribution flattens to $n \propto r^{-1.4}$.
2. There exists a dominant population of massive young stars, dynamically unrelaxed blue supergiants with He emission lines in their IR spectra (the He emission line stars).
3. These He emission line stars appear to be Wolf-Rayet stars or Luminous Blue Variables with masses of 10's M_odot and lifespans of $\sim 10^6$ y.
4. These stars belong to two intersecting orbits, strongly inclined to each other and to the Galactic rotation.

1.3 Beyond the Central Parsec

1. Beyond the central parsec, which is generally evacuated of gas, lies the Circumnuclear Disk
2. The Circumnuclear Disk extends from from $r \sim 1$ pc to ~ 7 pc containing dense ($n > 10^4$ cm$^-3$) molecular clouds.
3. The Circumnuclear Disk may arise from tidal capture and shearing of molecular clouds that have been scattered onto low angular momentum orbits (in some cases with an opposite sense of rotation with respect to the Galaxy) by cloud-cloud collisions.

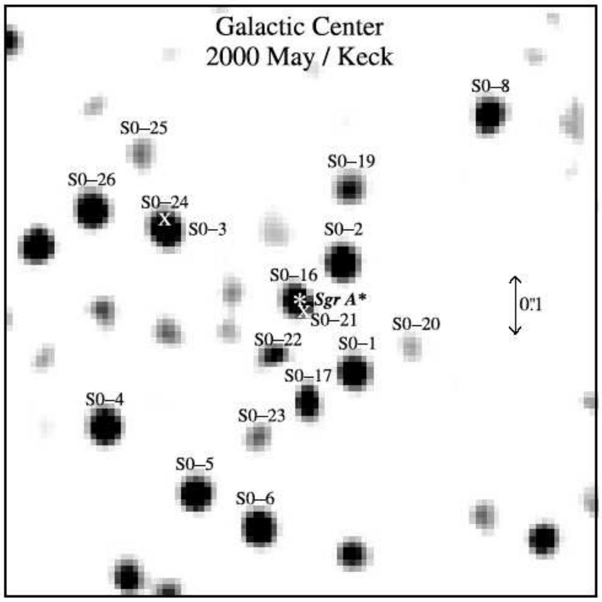

Figure 1: The S-stars in the central 1" by 1" around the Galactic Center. From Ghez et.al. 2005.

4. Outside of 0.4 pcm the stellar population matches smoothly to the stellar density profile of $n \propto r^{-2}$ characteristic of the inner 100 pc.
5. The stellar distribution is a mix of old and young stars.

1.4 General Numbers

1. Parameters
   (a) Distance to GC, $R = 8.0$ kpc
   (b) Black Hole Mass, $M_{BH} = 3.7 \times 10^6 M_\odot$
   (c) Schwarschild Radius, $R_s = 1.1 \times 10^{12}$ cm $= 0.073$ AU $= 3.6 \times 10^{-7}$ pc
   (d) Tidal Radius, $R_t = 2 \times 10^{13}$ cm $= 1.5$ AU $= 7 \times 10^{-6}$ pc
   (e) Sphere of Influence of BH, $r_h \sim 10^{19}$ cm $= 3$ pc
2. Conversions
   (a) At a distance of $R = 8.0$ kpc,
      i. 1 mas $= 1.16 \times 10^{14}$ cm $= 7.76$ AU $= 3.9 \times 10^{-5}$ pc
      ii. $1'' = 1.16 \times 10^{17}$ cm $= 7.76 \times 10^3$ AU $= 0.04$ pc
      iii. $1'' = 46$ light days
      iv. $1 \frac{\text{mas}}{\text{y}} = 36.7 \frac{\text{km}}{\text{s}}$
   (b) Solar Mass, $1 M_\odot = 2 \times 10^{33}$ g
   (c) Solar Radius, $1 R_\odot = 7 \times 10^{10}$ cm
   (d) 1 pc $= 3.08 \times 10^{18}$ cm

   (e) 1 AU $= 1.5 \times 10^{13}$ cm
   (f) Gravitational Constant, $G = 6.67 \times 10^{-8} \frac{\mathrm{cm}^3}{\mathrm{g\ s}^2}$

3. Formulas
   (a) Schwarschild Radius, $R_s = \frac{2GM}{c^2}$
   (b) Schwarschild Radius, $R_t = r \left(\frac{M}{m}\right)^{1/3}$

2 Possible Origins of the S-Stars

1. Old stars that appear young
2. Formed in situ in the extreme near black hole environment
3. Formed elsewhere but migrated rapidly to the center

3 Older Stars that Appear Young

3.1 Stellar Mergers

1. Several mergers are likely necessary to reach S-star masses
2. For more massive merger products, the lifetimes decrease
   (a) For this reason mergers are not likely to be the explanation of the He emission line stars
   (b) For the S-stars, the higher stellar density, smaller masses (B-stars) to be created, and shorter collision times make this scenario more likely
3. The velocity dispersion of stars $\sigma \sim 400$ km/s at $r = 0.01$ pc is comparable to the escape velocity from an O9.5 star (~ 1000 km/s
   (a) Mergers at such high energies may involve significant mass loss, making the accumulation of B-star masses more difficult
4. The rotation rate of S0-2 appears to be normal for a B-star in the solar neighborhood
   (a) Merger products are expected to be more rapidly rotating due to conservation of angular momentum
   (b) Is S0-2 alone as a “normal” rotator, or do the other S-stars show the same rotation?

3.2 Exotic Objects

1. It is expected that stellar black holes and neutron stars will sink into the central few mpc due to dynamical mass segregation
2. Thorne-Zytkow objects may form in the collision of a stellar remnant with a normal star
3. Neutron star and star merger
   (a) Expected to become a red giant or supergiant
   (b) May be unstable

4. White Dwarf and star merger
    (a) Stellar remnant can be "reborn" and form a stable star
    (b) More likely to become a red giant
    (c) But White Dwarves are likely to have migrated out of the central region through dynamical mass segregation

3.3 Stripped Red Giants

1. Collisions or tidal stripping can remove the envelope of red giants, exposing the hot core
2. There is a signifcant lack of red giants in the inner 0.2 pc.
3. But, the luminosity of the exposed stellar cores may be too small to appear as normal B-stars

3.4 Evidence from Blue Stragglers

1. It is unclear if a merger event would necessarily leave evidence of its violent history
2. The lack of unusual spectral features of the S-stars does not strongly constrain their origin

4 In Situ Formation

4.1 Star Formation sparked by violent compression

1. Precursor molecular clouds must exceed a critical density to avoid being torn apart by tidal forces
2. Tidal compression of radially moving clouds could help, giving compression in two dimensions, although radial distension mitigates this effect
3. Collisions of separate molecular clouds may give sufficient compressions to instigate star formation. The He line emission stars in the central parsec, but outside of the Sgr A^* cluster may be explained by this process
4. Violent events are expected to be a common occurence in the near massive black hole environment

4.2 Limit Cycle of Accretion from the Circumnuclear Disk

1. The circumnuclear disk contains dense ($n > 10^4$ cm$^-3$) molecular clouds extending from $r \sim 1$ pc to ~ 7 pc, but shows a cavity with little gas in the central pc.
2. Ram pressure from the stellar winds from the S-stars may be sufficient to evacuate and maintain this cavity
3. After the 10^7 y lifetime of the S-stars, this wind support will diminish and viscous effects in the circumnuclear disk will cause it to fill in the cavity.
4. If a cloud falls in toward the massive black hole, a burst of energy released in the onset of accretion can compress the surrounding clouds to stimulate a burst of star formation.
5. The luminous accretion and winds from newly born star will clear the central pc of gas once more, leaving a cluster of massive young stars.
6. What happens when these massive stars in the central cluster go supernova?
7. The magnitude of the compression necessary to spark star formation must be huge.

4.3 Cloud-cloud collisions to form the He emission linestars

1. In the region 0.04 pc $< r <$ 0.4 pc, the He emission line stars form two clear and distinct orbits.
2. If these stars form in a violent collision of two dense molecular clouds, these orbits may be ghosts of the original orbits of the two clouds.
3. If a single cloud fell towards the center with no angular momentum (after a cloud-cloud interaction at larger radii scattered it onto this orbit), could it form the S-stars after passing over the central massive black hole and being compressed by the ensuing accretion energy release?

5 External Formation Followed by Rapid Migration

5.1 Massive Star Cluster Migration

1. The migration time for individual stars by dynamical friction is much greater than the S-star lifetime of 10 My.
2. But, for massive clusters of 10^5–$10^6 M_\odot$, dynamical friction can realize rapid migration on timescales $t < 10^7$ My.
3. Core collapse appears inevitable in these massive clusters
4. Stars outside the core will be tidally stripped as the cluster migrates inward
5. No such large clusters are observed with the central pc.

5.2 Intermediate Mass Black Holes

1. Core collapse in such a massive star cluster may produce an intermediate mass black hole
2. The He emission line stars could have arisen by tidal stripping from the intermediate mass black hole
3. But, such a cluster would deposit these massive stars at all radii along its infall, but no such stars are seen beyond the central pc

5.3 Tidal Disruption of Closely Passing Binaries

1. Massive star binaries (perhaps related to the He emission line stars) passing closely by the massive black hole can be disrupted, leaving one member tightly bound to the massive black hole
2. But further multiple scattering encounters with other star would be necessary to decrease the apoapse distances to within the observed range in the S-star cluster.

5.4 Other Issues

1. Both inspiralling cluster and in situ formation would tend to form a disk of stars because of angular momentum in the system
    (a) If an errant cloud had little angular momentum, could the isotropic Sgr A* cluster be explained by Star Formation driven by compression of the cloud as it surrounds the massive black hole and begins to accrete?

(b) If the S-stars and He emission line stars all formed at once, the isotropy of the S-stars could be explained by Lens-Thirring precession.

   i. But such a process would produce angular momentum vectors of the S-stars in a plane, in contrary to observations

   ii. Nor can Lens-Thirring precession produce low angular momentum orbits from orbits such as those of the He emission line stars.