2015.07.24 astro-ph Seminar (担当 大澤)

Impact of the initial disk mass function on the disk fraction

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Abstract & Introduction

The disk fraction, the percentage of stars with disks in a young cluster, is widely used to investigate the lifetime of the protoplanetary disk, which can impose an important constraint on the planet formation mechanism. The relationship between the decay timescale of the disk fraction and the mass dissipation timescale of an individual disk, however, remains unclear. Here we investigate the effect of the disk mass function (DMF) on the evolution of the disk fraction. We show that the time variation in the disk fraction depends on the spread of the DMF and the detection threshold of the disk. In general, the disk fraction decreases more slowly than the disk mass if a typical initial DMF and a detection threshold are assumed. We find that, if the disk mass decreases exponentially, the mass dissipation timescale of the disk can be as short as $1\,\mathrm{Myr}$ even when the disk fraction decreases with the time constant of $\sim 2.5\,\mathrm{Myr}$. The decay timescale of the disk fraction can be an useful parameter to investigate the disk lifetime, but the difference between the mass dissipation of an individual disk and the decrease in the disk fraction should be properly appreciated to estimate the timescale of the disk mass dissipation.

Key words: protoplanetary disks — stars: protostars — stars: statistics

- **統計量を扱ううえでの注意喚起**
- protoplanetary disk の年齢は planet formation process を決めるうえで重要
  - NIR や MIR では disk は optically thick なので disk mass の減衰を調べられない
  - 若い天体の年齢を個別に求めるのは難しい (~1-5 Myr の誤差がついて回る)
- 星団内で disk が受かっている天体の割合 (disk fraction) と星団の年齢で議論することが多い
- disk fraction の減衰タイムスケールの意味は何か？**(disk mass function の影響を調べた)**

簡単な仮定を置いて観測をモデル化

Disk Mass Function の定義

これは $\int \phi_0(m_\mathrm{d})\mathrm{d}m_\mathrm{d} = 1$ を満たす

$$\phi_0(m_\mathrm{d})\mathrm{d}m_\mathrm{d} = \frac{1}{m_\mathrm{d}\sqrt{2\pi}\sigma}\exp\left[-\frac{1}{2}\left(\frac{\log m_\mathrm{d} - \log\mu}{\sigma}\right)^2\right]\mathrm{d}m_\mathrm{d}$$

σとμは観測的に決まっている量を採用する

Disk Mass の減衰の仕方を定義(単調減少)

Z(m) は m の単調増加関数になる

$$\frac{\mathrm{d}m_\mathrm{d}}{\mathrm{d}t} = -\frac{1}{\zeta(m_\mathrm{d})} \Rightarrow -t = \int_{m_\mathrm{d}(0)}^{m_\mathrm{d}(t)} \zeta(m)\mathrm{d}m = \mathcal{Z}\left(m_\mathrm{d}(t)\right) - \mathcal{Z}\left(m_\mathrm{d}(0)\right)$$

ζ > 0 として単調減少を仮定

時刻 t のある disk の質量は初期質量と時間 t のみに依存

$$\Rightarrow m_\mathrm{d}(t) = \mathcal{M}\left(t, m_\mathrm{d}(0)\right) = \mathcal{Z}^{-1}\left(-t + \mathcal{Z}\left(m_\mathrm{d}(0)\right)\right)$$

$f^\mathrm{ex} > f^\mathrm{th}$ ならば disk が検出されるとする,

disk からの flux は disk の質量について単調増加すると仮定

$\Rightarrow f^\mathrm{ex}(m_\mathrm{d}^\mathrm{th}) = f^\mathrm{th}$ を満たす質量 m_d^th が存在

disk が観測的にうかるかどうかは disk 質量だけで決められる

Disk Fraction の定義

$$\mathcal{F}(t) = \int_{m_\mathrm{d}^\mathrm{th}}^{\infty} \phi_t(m)\mathrm{d}m \Rightarrow \mathcal{F}\left(t;\, m_\mathrm{d}^\mathrm{th}, \mu, \sigma\right) = \frac{1}{2}\mathrm{erfc}\left[\frac{\log\mathcal{M}\left(-t, m_\mathrm{d}^\mathrm{th}\right) - \log\mu}{\sqrt{2}\sigma}\right]$$

※ erfc は complementary error function

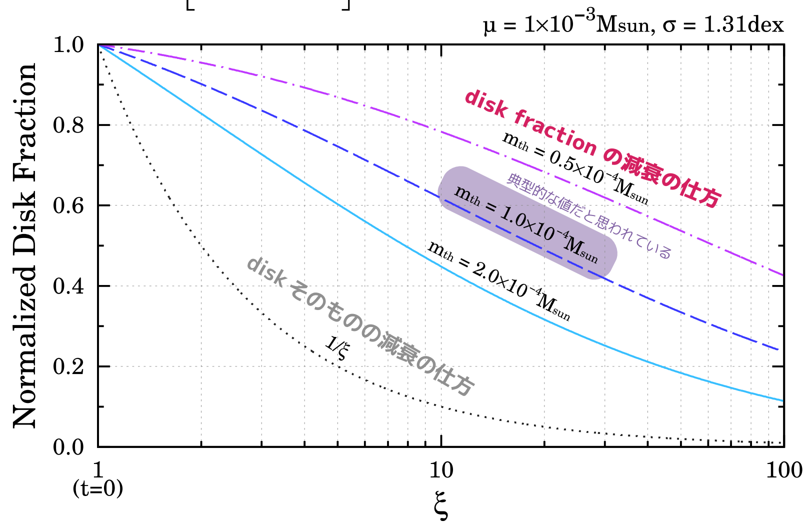
①一般的な場合

最も一般的な仮定で disk fraction の減衰と disk 質量の減衰を比較

最初に threshold mass よりも ξ 倍重たかった disk が見えなくなるまでの時間

$$\mathcal{M}\left(T(\xi), \xi m_\mathrm{d}^\mathrm{th}\right) = m_\mathrm{d}^\mathrm{th} \leftrightarrows T(\xi) = \mathcal{Z}\left(\xi m_\mathrm{d}^\mathrm{th}\right) - \mathcal{Z}\left(m_\mathrm{d}^\mathrm{th}\right)$$

$$\mathcal{F}\left(T(\xi); m_\mathrm{d}^\mathrm{th}, \mu, \sigma\right) = \frac{1}{2}\mathrm{erfc}\left[\frac{\log\left(\xi m_\mathrm{d}^\mathrm{th}/\mu\right)}{\sqrt{2}\sigma}\right]$$



nominal な disk mass function の形状を仮定して計算すると
"一般に" disk fraction の減衰は disk 質量そのものの減衰よりも遅い
disk fraction の減衰 timescale は disk 散逸の timescale より常に長く出る

②指数的減衰を仮定

観測で得られた disk fraction を再現するようなパラメタを計算してみる

exponential decay を仮定した時の Disk Fraction の変化

$$m_\mathrm{d}(t) = m_\mathrm{d}(0)\mathrm{e}^{-\frac{t}{\tau}}$$

$$\phi_t(m_\mathrm{d})\mathrm{d}m_\mathrm{d} = \frac{1}{m_\mathrm{d}\sqrt{2\pi}\sigma}\exp\left[-\frac{1}{2}\left(\frac{\log m_\mathrm{d} - \log\mu\mathrm{e}^{-\frac{t}{\tau}}}{\sigma}\right)^2\right]\mathrm{d}m_\mathrm{d}$$

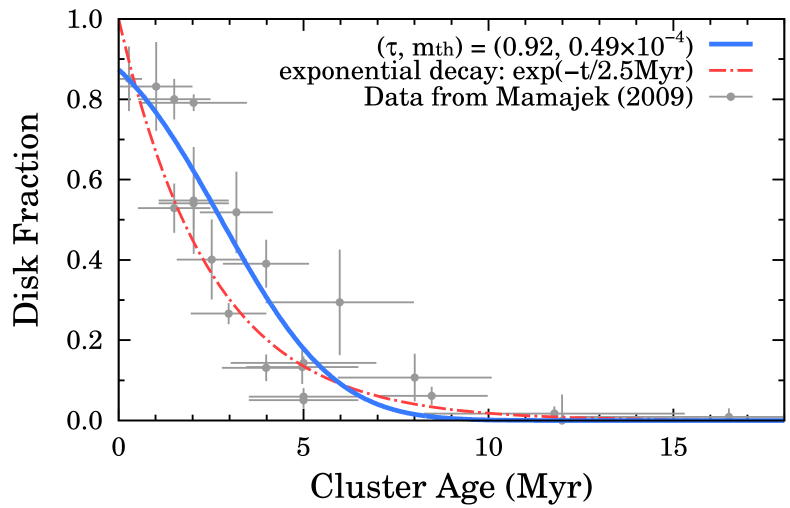


Fig. 3. Comparison with observed disk fractions. The gray filled circles with errors are observed disk fractions from Mamajek (2009). The blue solid line shows the disk fraction with the best-fit parameters. The red dot-dashed line shows an exponential decay with a time constant of $2.5\,\mathrm{Myr}$.

単純に exponential fit すると disk fraction は 2.5Myr 程度で減衰 (Mamajek, 2009)
disk mass function の影響を考慮すると disk 質量は 1Myr 程度で減衰している可能性