広視野・高頻度サーベイと即時フォローアップによる新星初期の観測可能性

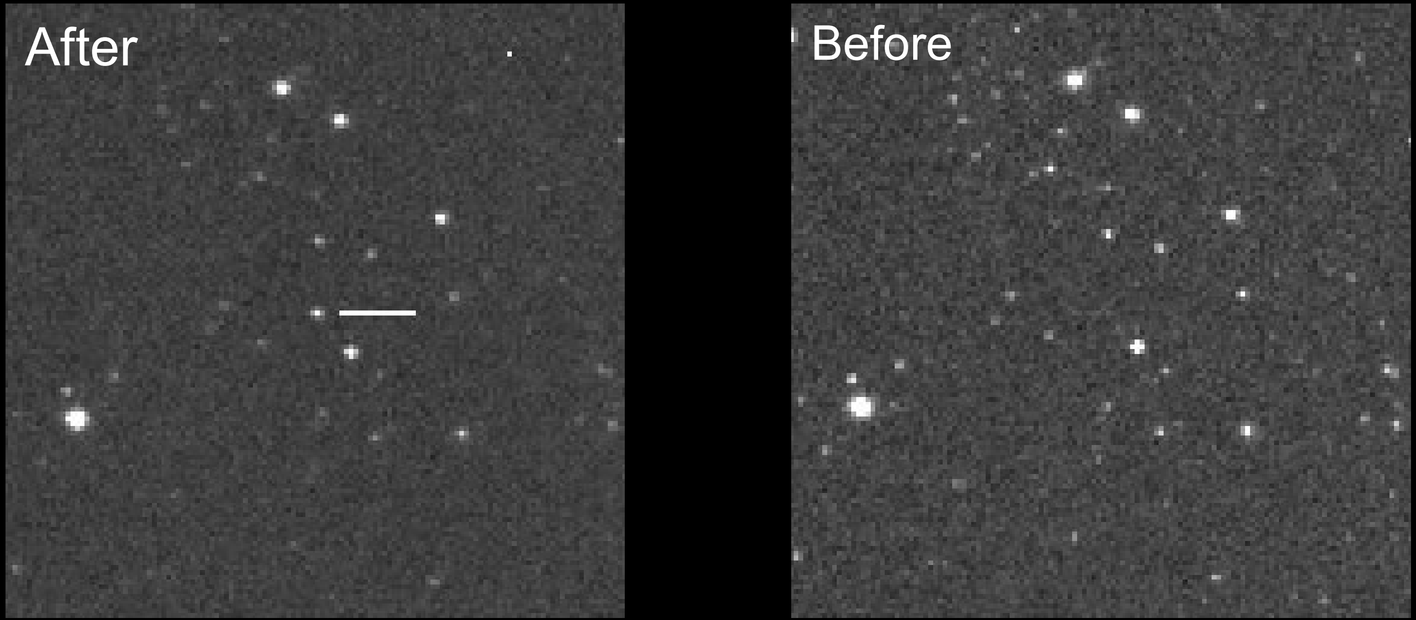
2022/7/5 (木曽シュミットシンポジウム)

田口健太 (京大 D3)

(Classical) Novae: (古典) 新星、新星爆発

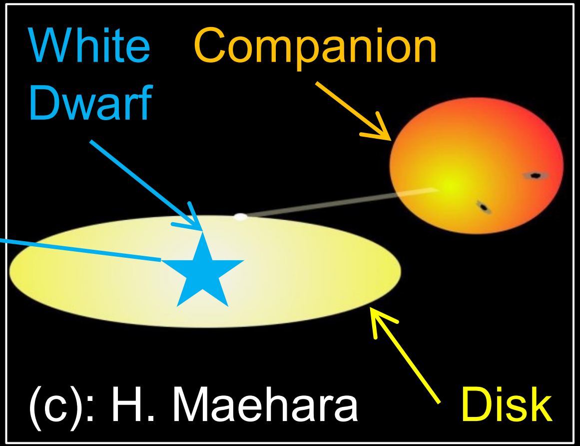
- “Nova” とはラテン語で “new star” の意味
- **「新しい」星が突然 (多くの場合 ~ 1 day 以内で) 出現**する
- 宇宙物理学的には、これも突発天体現象

V1405 Cas (by Yuji Nakamura)



新星爆発を起こす要因
(Thermonuclear Runaway, 熱核暴走反応)

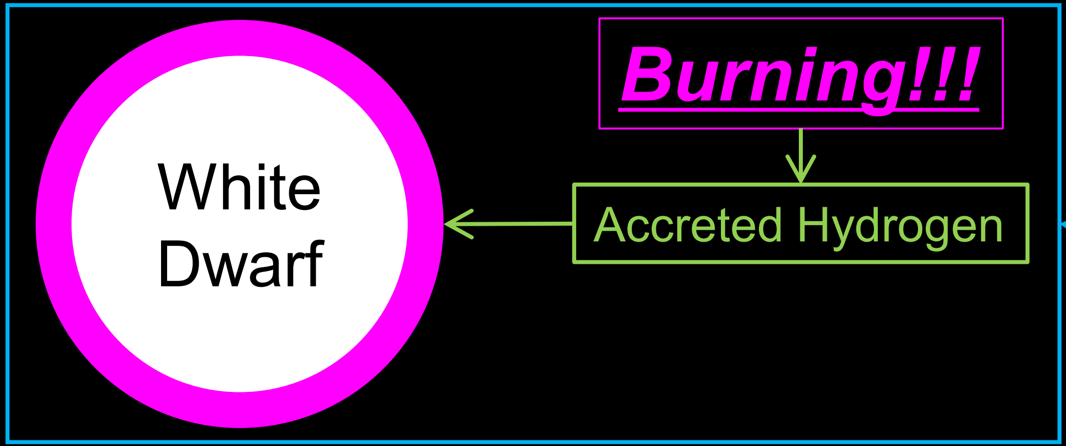
- **白色矮星 (WD, 主星)** と **晩期型星 (伴星, companion)** から成る連星系
  (e.g., 激変星 (novalikes, 矮新星, polars, など) や共生星などが該当)
- **伴星**由来のガスが**白色矮星表面**に降着し、**水素ガス**の層を形成

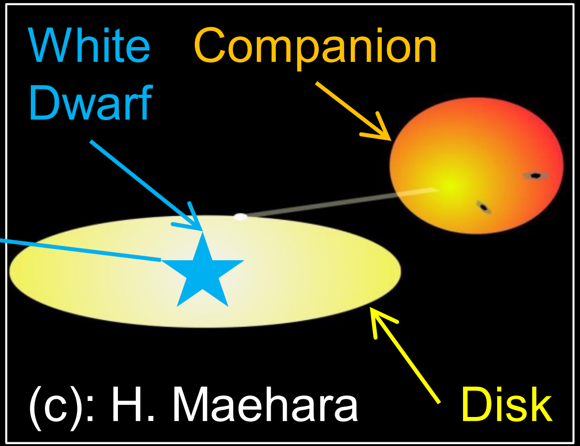


- ガスが溜まれば溜まるほど、水素ガス層の温度・密度は高まる
  → 突然**核反応**が始まり、新星を引き起こす

新星爆発を起こす要因 (Thermonuclear Runaway, 熱核暴走反応)

- **白色矮星 (WD, 主星)** と **晩期型星 (伴星, companion)** から成る連星系
  (e.g., 激変星 (novalikes, 矮新星, polars, など) や共生星などが該当)
- **伴星**由来のガスが**白色矮星表面**に降着し、**水素ガス**の層を形成

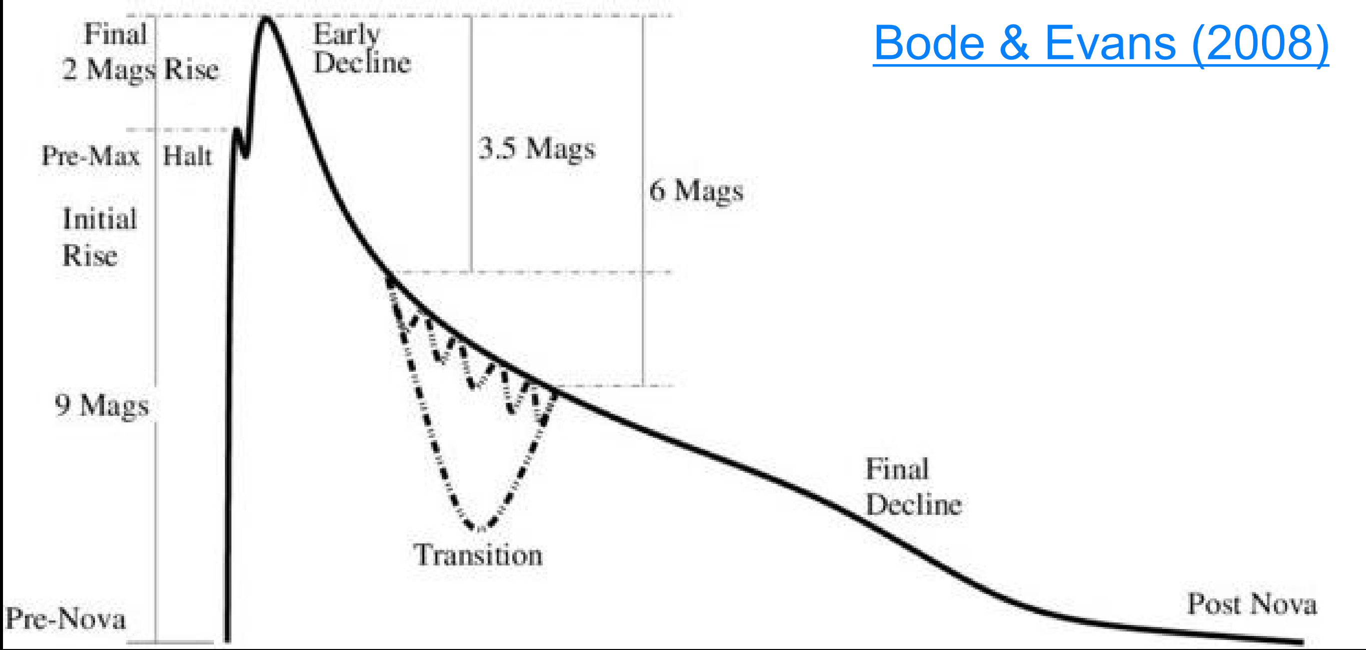




- ガスが溜まれば溜まるほど、水素ガス層の温度・密度は高まる
  → 突然**核反応**が始まり、新星を引き起こす

可視光での light curve

- 図: 典型的な光度曲線
  - **最初の 1 日くらいで**「initial rise」
    - (分光) 観測が難しい
  - 典型的には数週間 ~ 数年で暗くなる
    (暗くなる間の観測は簡単)

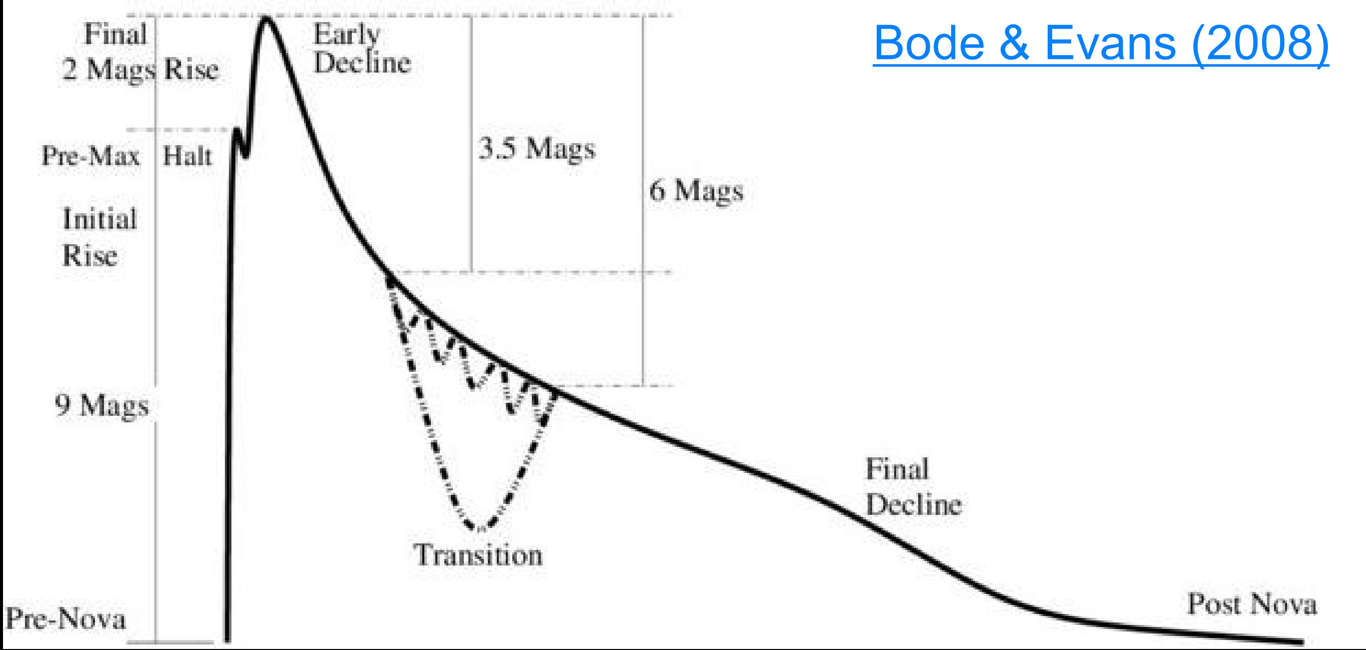


[Bode & Evans (2008)]

- ざっくり ~ **10 等くらいの増光**幅
  (最低でも ~ 7 等、最高だと ~ 19 等)
- 絶対等級 $M_{V,peak}$ ~ – 6 to – 10
  - 銀河系内 (+ M31 など) が観測対象 → **銀河面上に集中**して発生。

可視光での light curve

- 図: 典型的な光度曲線
  - **最初の 1 日くらいで**「initial rise」
    - (分光) 観測が難しい
  - 典型的には数週間 ~ 数年で暗くなる
    (暗くなる間の観測は簡単)



- ざっくり **~ 10 等くらいの増光**幅
  (最低でも ~ 7 等、最高だと ~ 19 等)
- 絶対等級 $M_{V,peak}$ ~ – 6 to – 10
  - 銀河系内 (+ M31 など) が観測対象 → **銀河面上に集中**して発生。

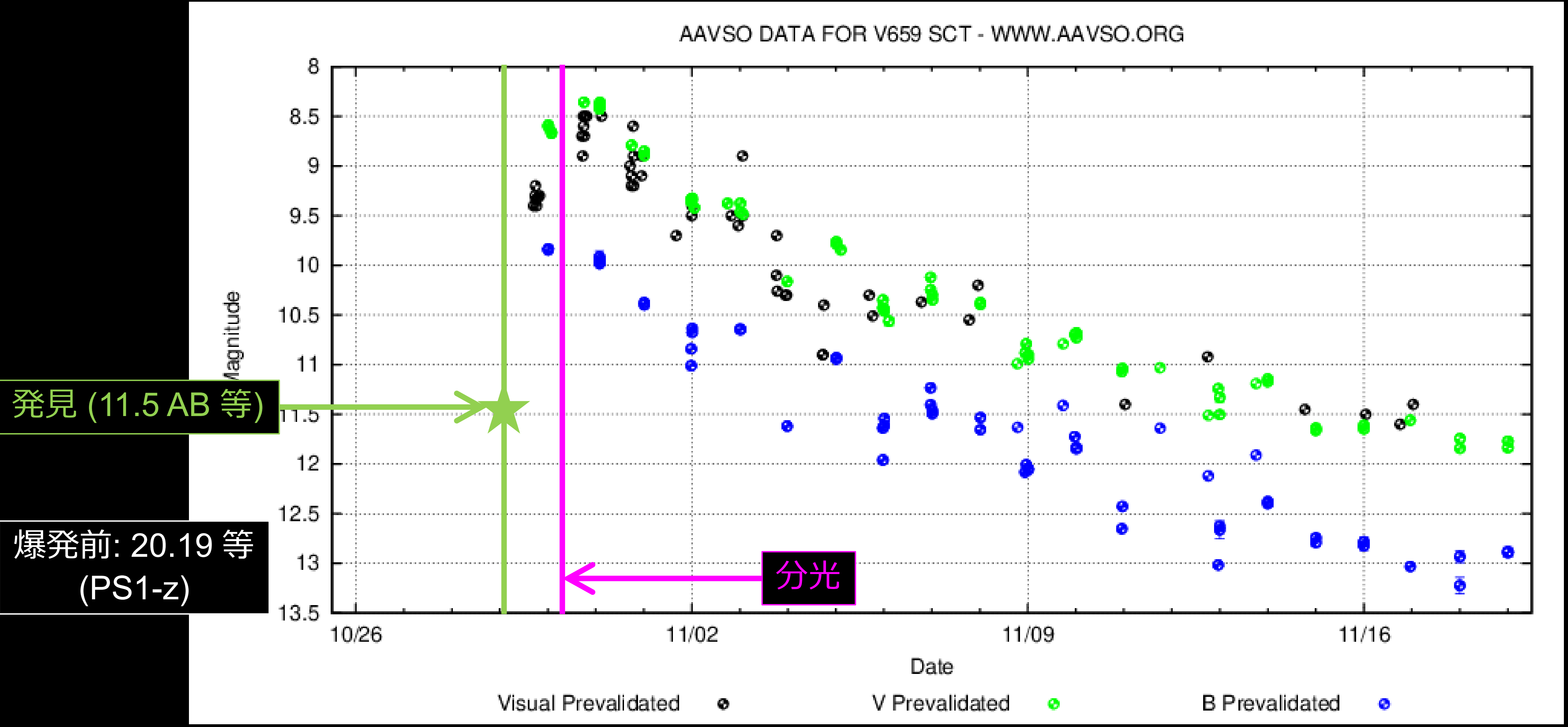
反復新星
(Recurrent Novae, 再帰新星なども)

- 新星爆発後、連星系が降着を再開 → **将来再び新星が起きるはず**
  - 多くの新星は 10^4 年とか極めて長い間隔で起きると考えられている
  - しかし、白色矮星が重いか、降着率が高いと、間隔は短くなる

- 反復新星: **史上複数回の新星爆発が記録されている天体**。
  - 銀河系内では 10 天体くらい知られている
  - いち早く爆発開始を発見すべく、アマチュアなどの監視対象
    - RS Oph: 1898, 1907, …, 1985, 2006, 2021
    - U Sco: 1863, ..., 1999, 2010, 2022
    - T CrB: 1866, 1946, (2020s?)

    など。

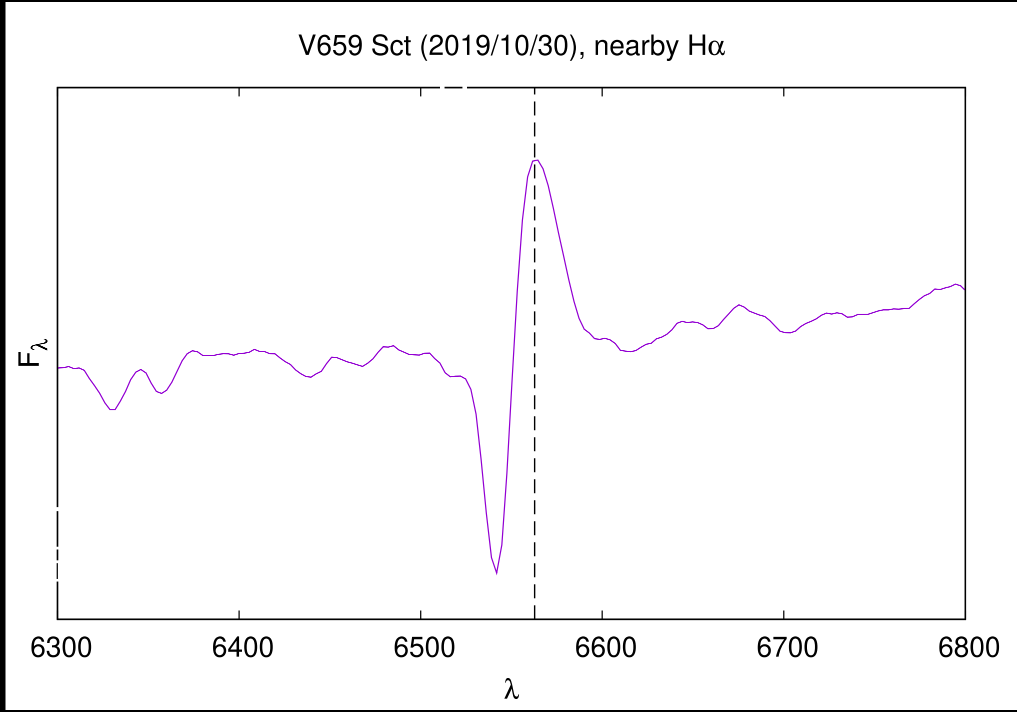
極大付近 (発見 1 日後) に分光した新星 V659 Sct の Light Curve



爆発前: 20.19 等 (PS1-z)

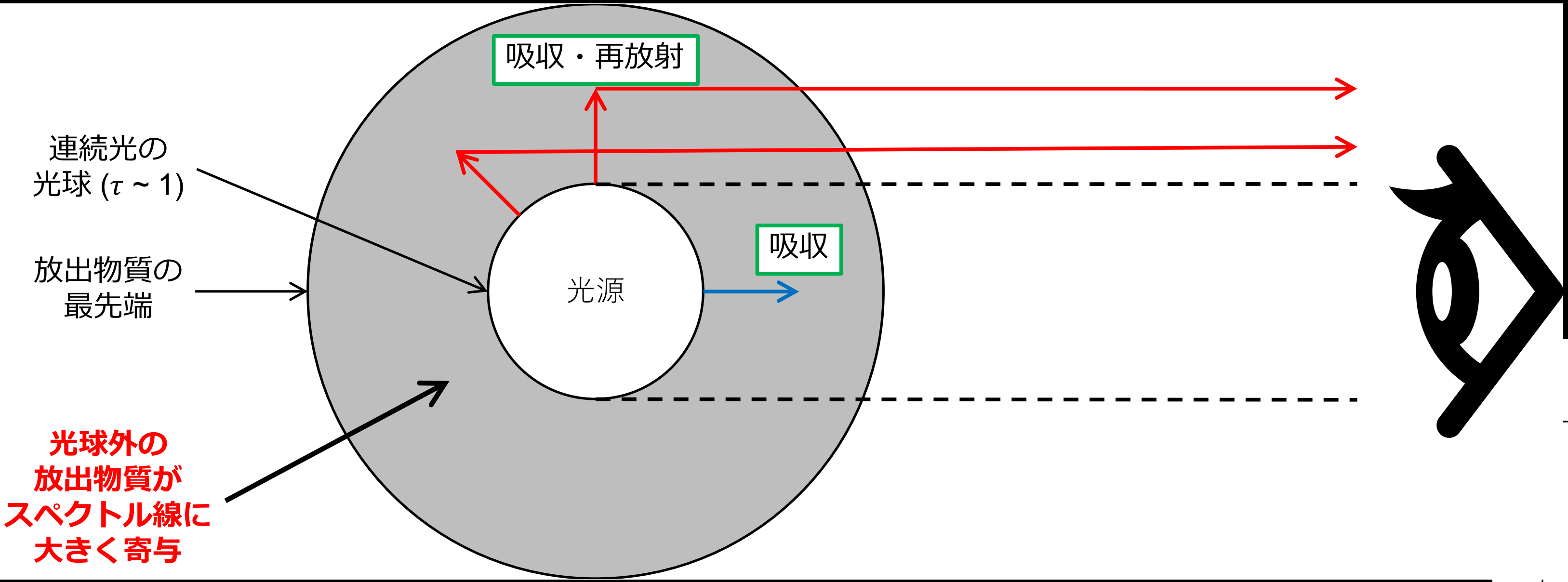
極大付近 (発見 1 日後) の新星スペクトル

- H I, He I, Fe II などの line が頻出
  - (後述の天体より) **電離階数は低い**
- **P Cygni 型の line** がよく見られる
  - 青方偏移した吸収成分
  - ほぼ静止波長の輝線成分

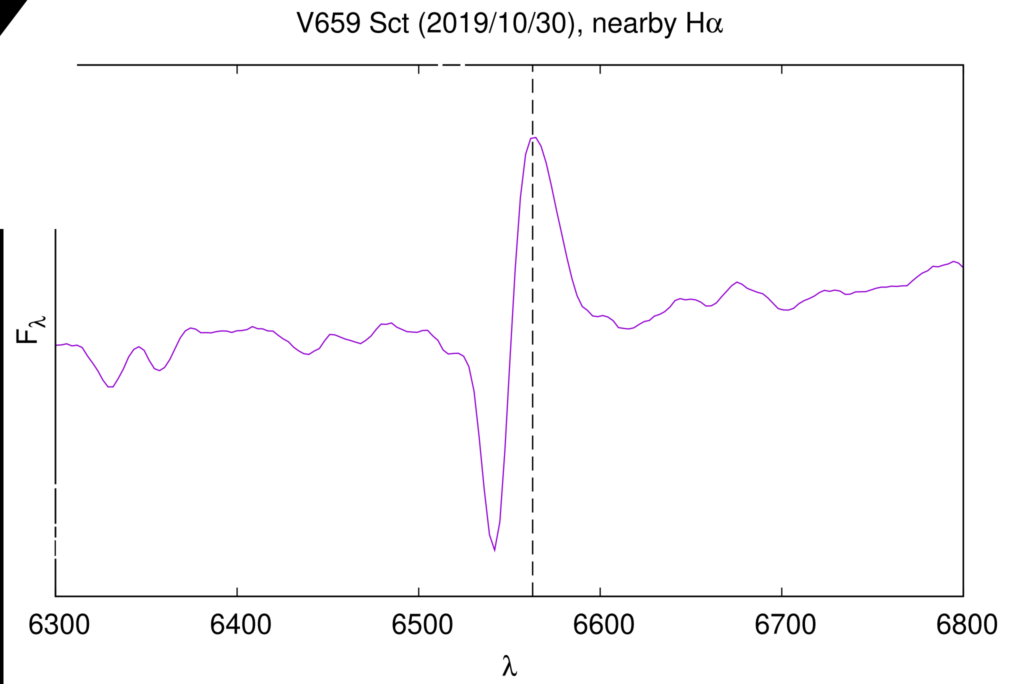


- P Cygni 型の line は (line に対し) **光学的に厚い膨張系を示す**
  - 何もなければ光球面から光が届くだけ
  - もしも光球面の外に line に対して光学的に厚い層があれば
    - 我々に届く光は吸収されてしまう (吸収線)
    - 我々に届く予定ではなかった光が吸収再放射などで届く (輝線)
  - 膨張に伴う Doppler 効果で、吸収のみ青方偏移

極大付近 (発見 1 日後) の新星スペクトル



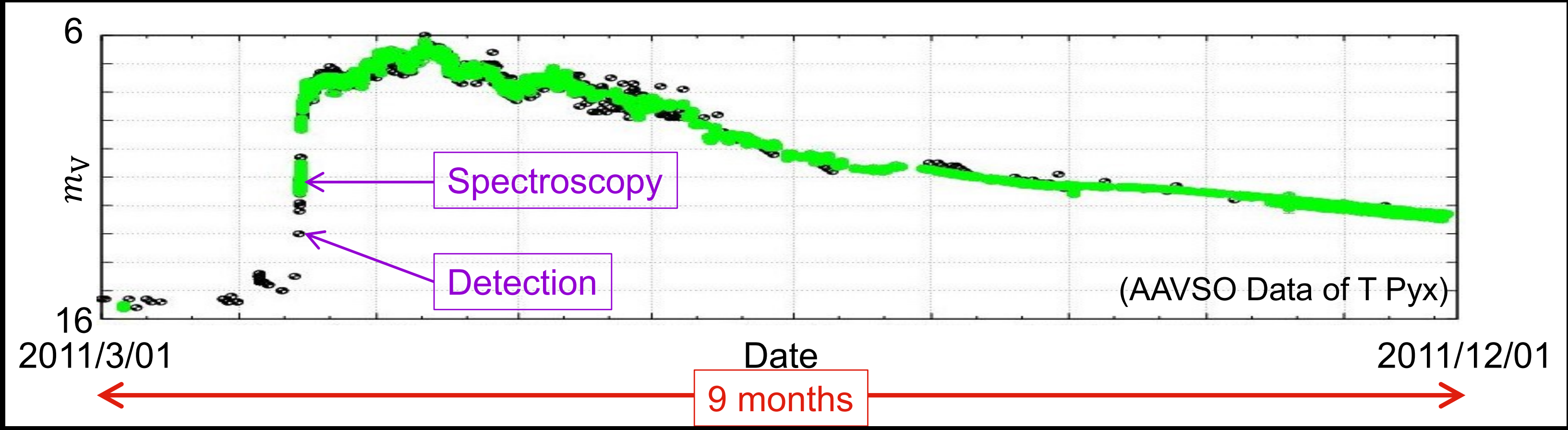
- H I, He I, Fe II などの line が頻出
  - (後述の天体より) **電離階数は低い**
- **P Cygni 型の line** がよく見られる
  - 青方偏移した吸収成分
  - ほぼ静止波長の輝線成分

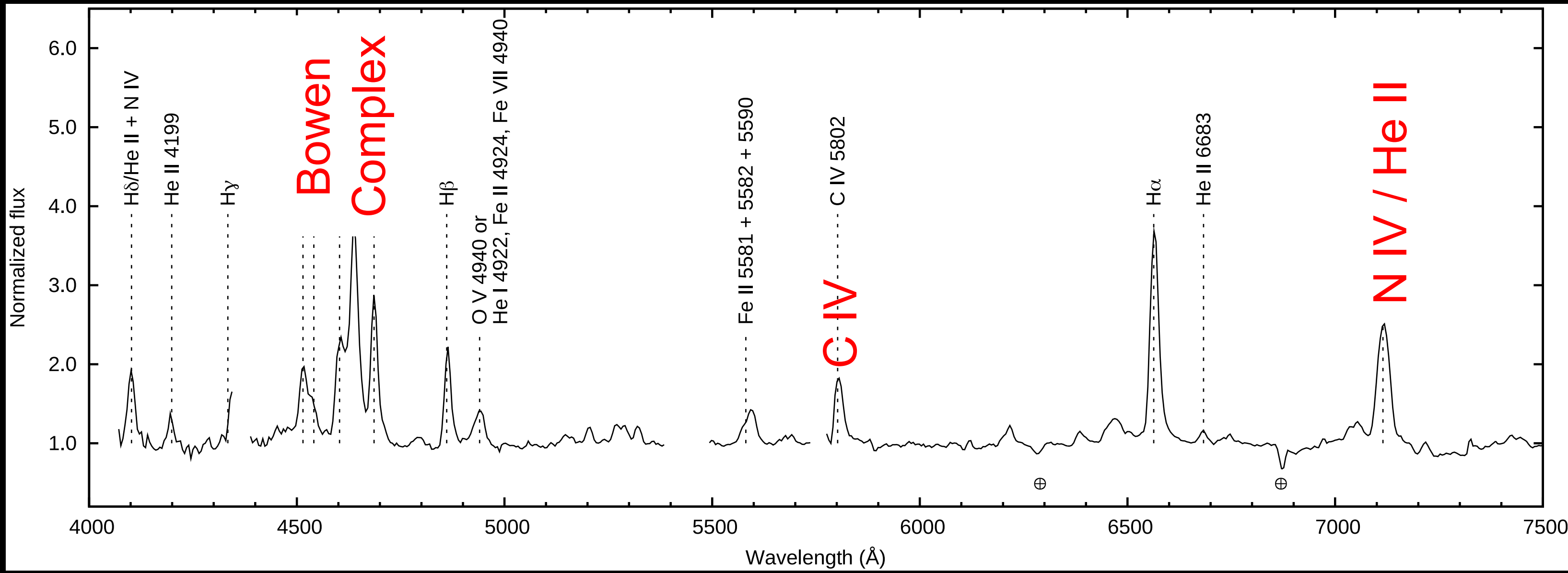


- P Cygni 型の line は (line に対し) **光学的に厚い膨張系を示す**
  - 何もなければ光球面から光が届くだけ
  - もしも光球面の外に line に対して光学的に厚い層があれば
    - 我々に届く光は吸収されてしまう (吸収線)
    - 我々に届く予定ではなかった光が吸収再放射などで届く (輝線)
  - 膨張に伴う Doppler 効果で、吸収のみ青方偏移

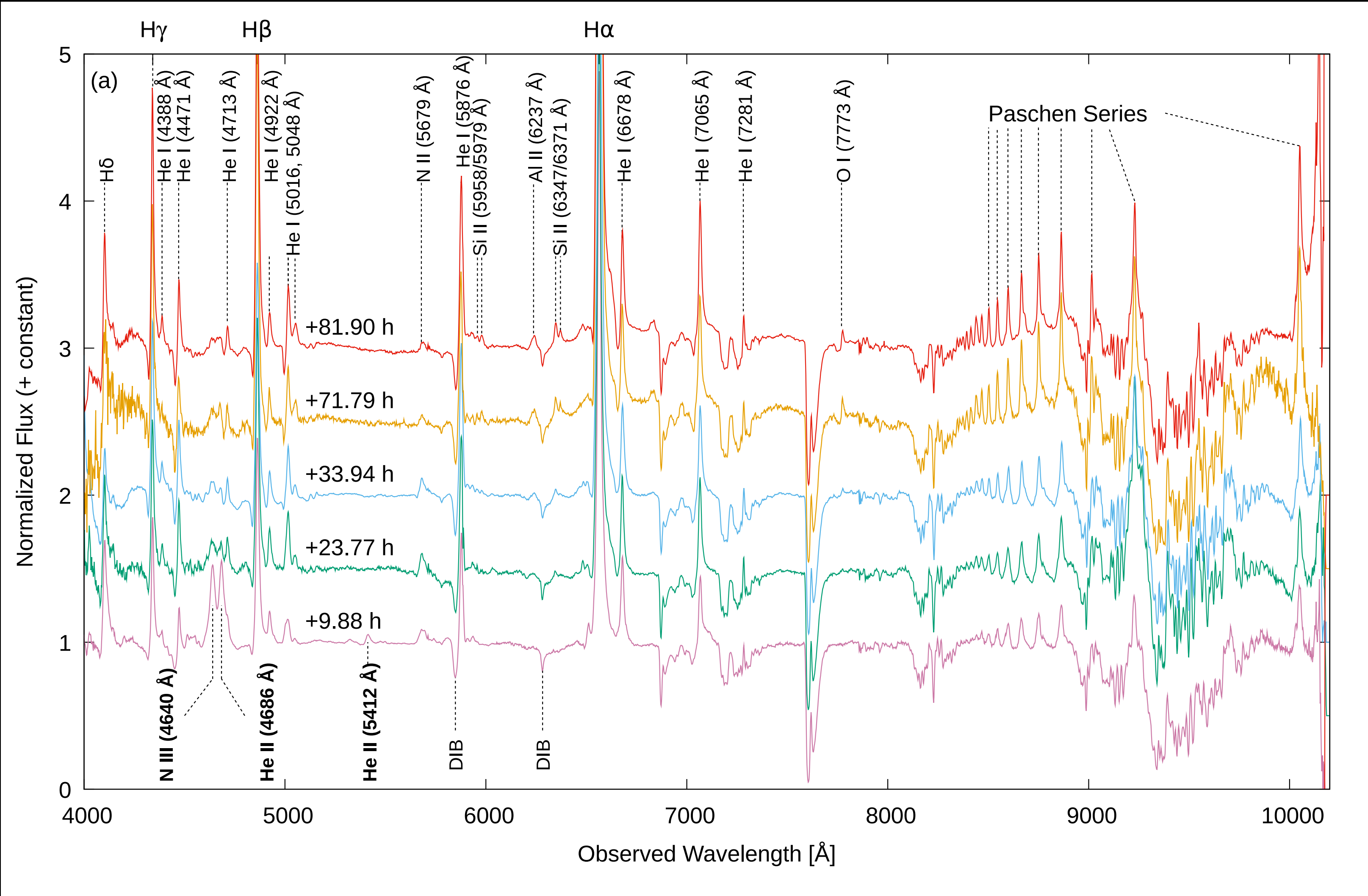
急増光期の反復新星 T Pyx (2011) の分光観測 (Arai et al. 2015)

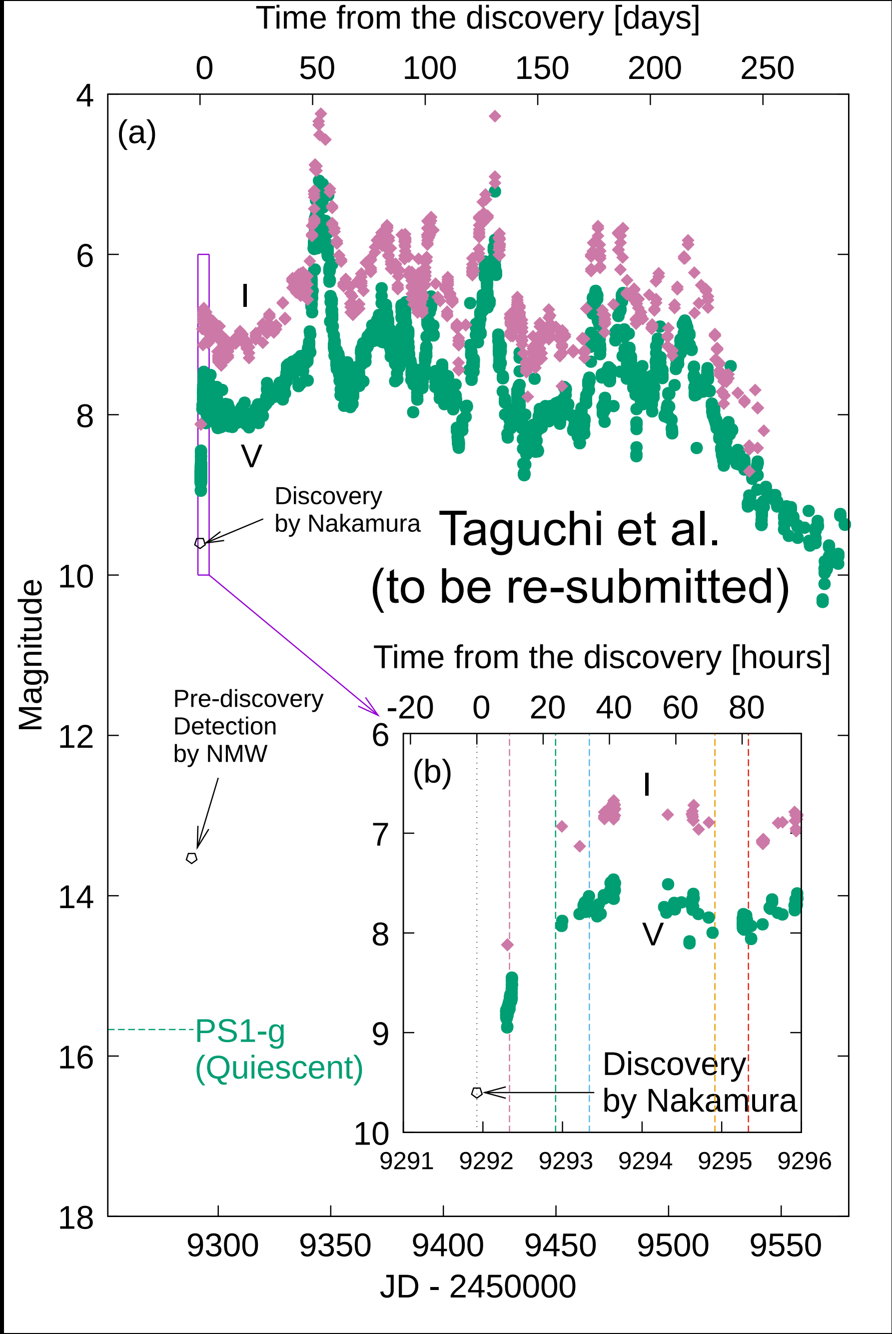
- 発見 0.19 日 (4.6 時間) 後に分光
  - 反復新星であったため、多くの人がモニターしていた
- 特徴
  - **高い電離階数の輝線**
    - 極大付近では消えた
    - 恐らく観測史上初?
  - **P Cygni 型の吸収なし**
  - 重力崩壊型超新星の "Flash spectroscopy" と類似



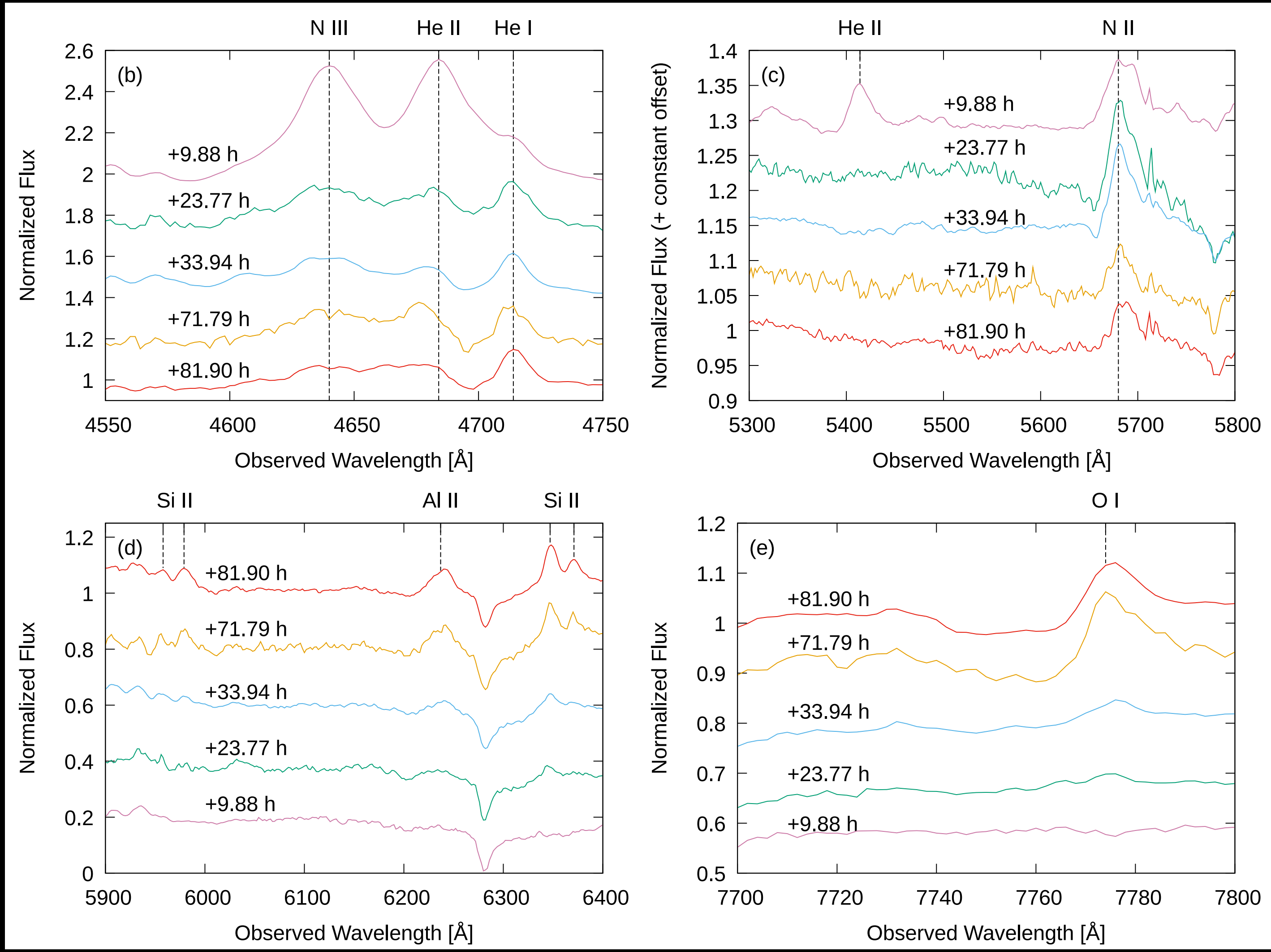


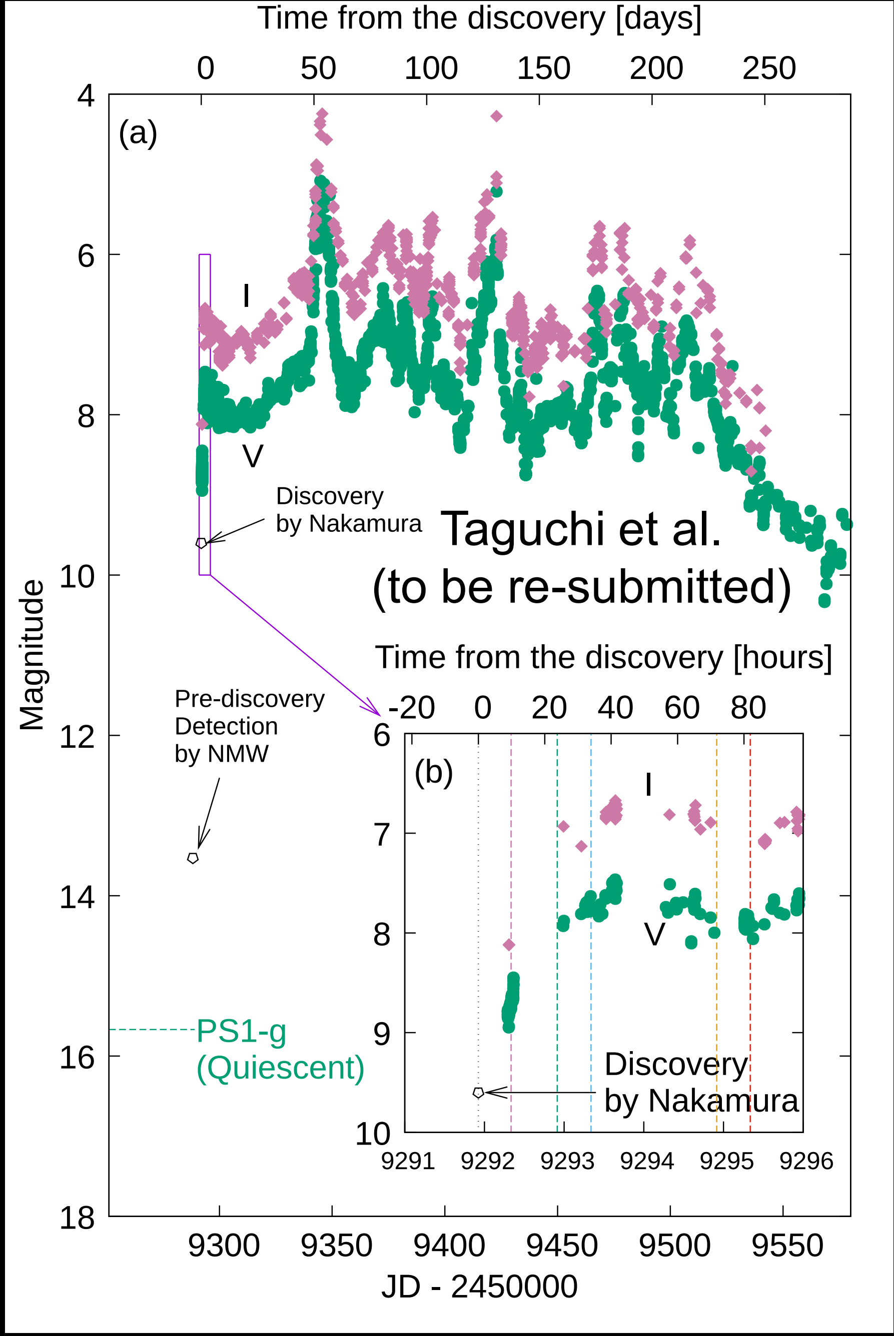
V1405 Cas の初期スペクトル (1)
Line の種類





V1405 Cas の初期スペクトル (1)
Line の種類

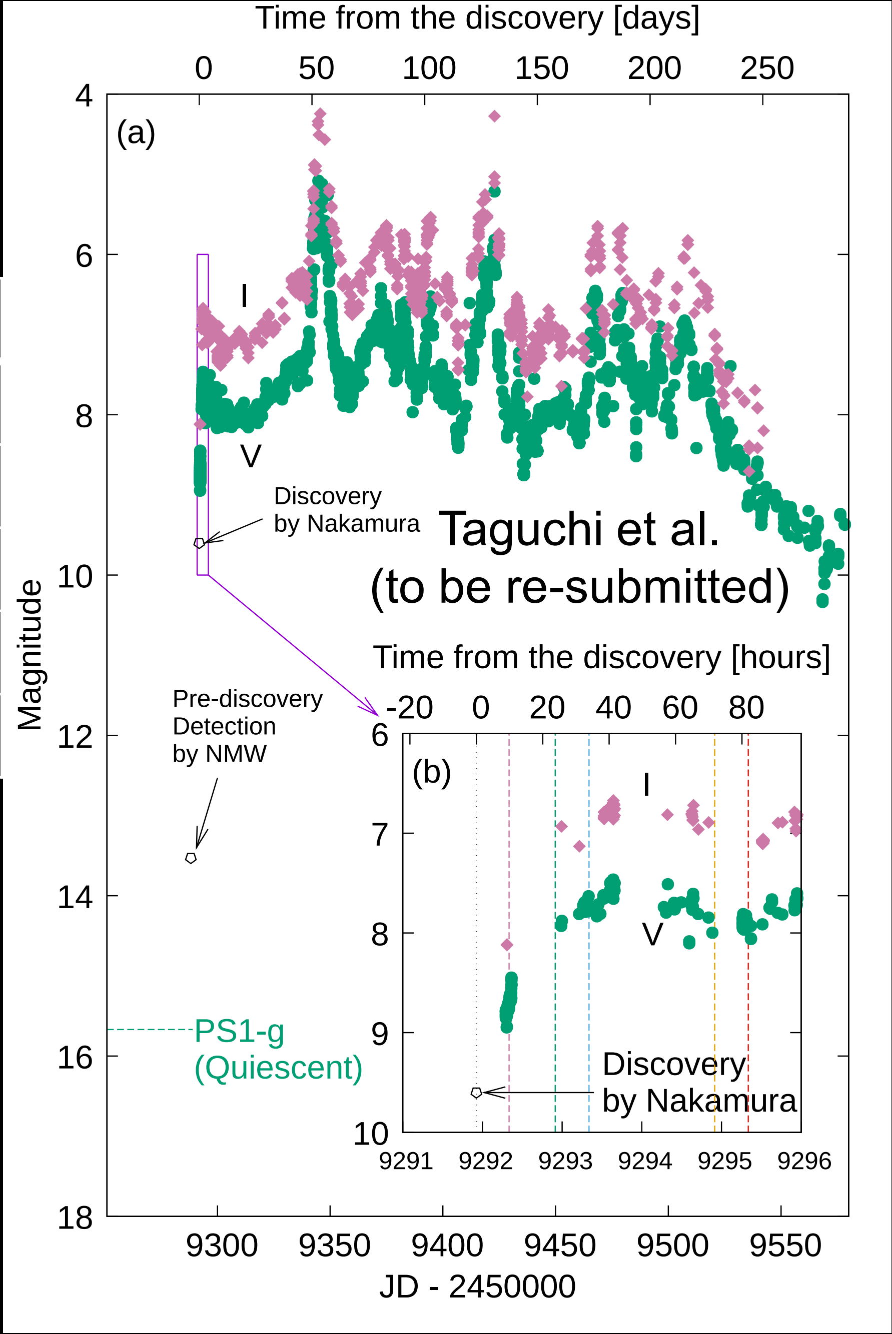




V1405 Cas の初期スペクトル (1) Line の種類

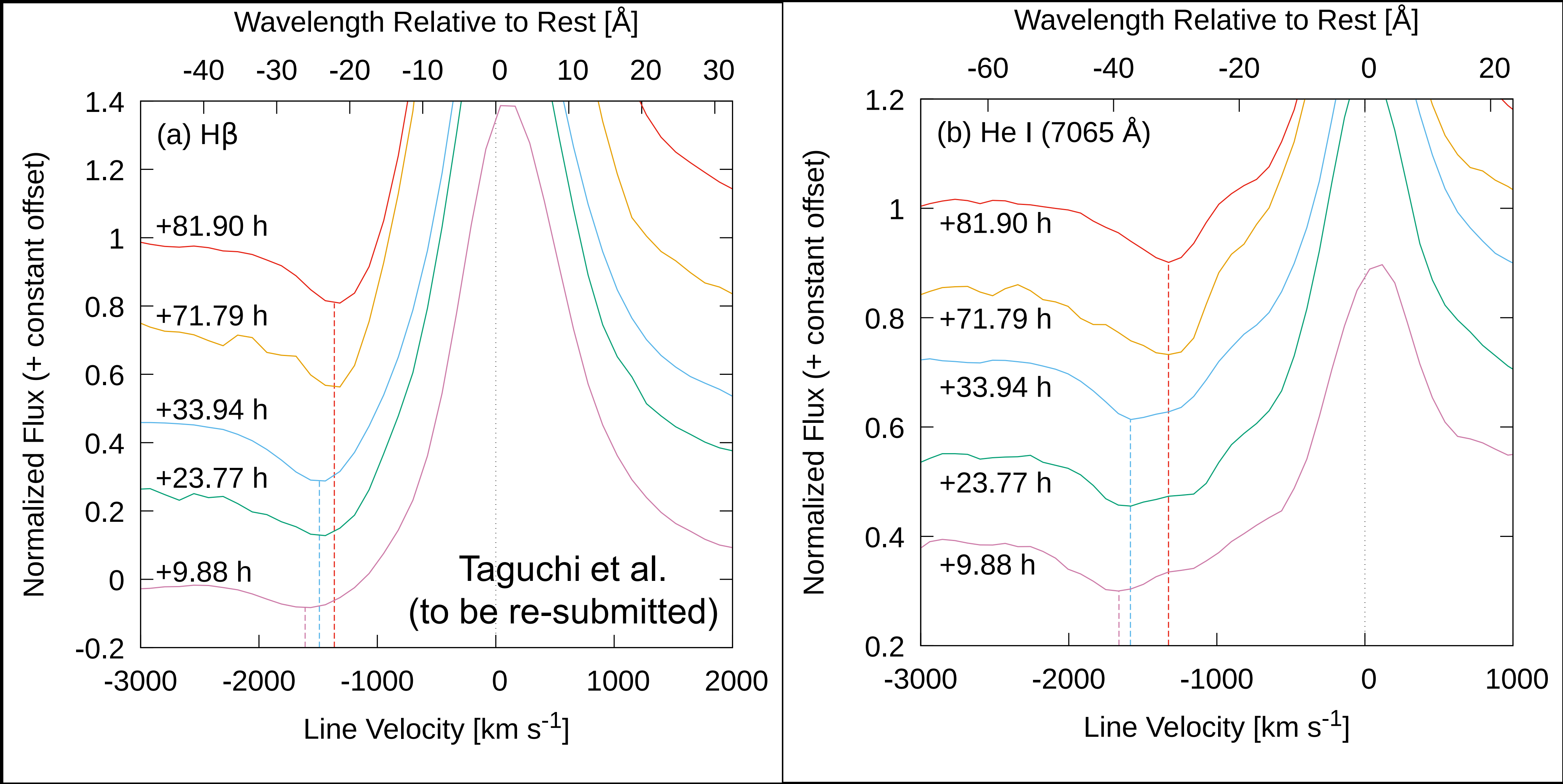
	N III	He II	N II	Si II	O I
+9.88 h	✓	✓	(✓)	×	×
+23.77 h	×	×	✓	(✓)	×
+33.94 h	×	×	✓	(✓)	×
+71.79 h	×	×	(✓)	(✓)	(✓)
+81.90 h	×	×	(✓)	(✓)	(✓)

- 高い電離階数 → 低い電離階数
  - T Pyx (Arai et al. 2015) とも consistent.
- 増光中は極めて温度が高かった



Initial Spectra of V1405 Cas (2): Line Absorption Velocities

- 減速



極大までの新星のスペクトル進化

- 恐らく T Pyx → V1405 Cas → 極大、の進化順
  - T Pyx (Arai et al. 2015)、発見 0.19 日 (4.6 時間) 後
    - **高い電離階数の line**: He II, C IV, N III, N IV
    - **P Cygni 型吸収なし**
  - V1405 Cas (Taguchi et al., to be re-submitted)、発見 9.88 時間後
    - **高い電離階数の line**: He II, N III (C IV, N IV は無し)
    - **P Cygni 型吸収あり。その速度は激しく減速**している
  - 極大付近
    - 温度は十分低下。
    - P Cygni の速度も割と落ち着き、タイムスケールは長くなる。
- 現在、物理的に解釈中 (Taguchi et al., to be re-submitted)
- 新星は千差万別 → **サンプルを増やす必要がある**と考えています。

新星の初期は面白い

- スペクトルも新星にしてはかなり特殊。

- 爆発に伴う物質の膨張もまだそこまで進んでいない
  → 系が ejecta に「汚染されてない」あるいは「食われてない」状態
  → 爆発直前の系の状態を探れるかも。
- 初期に γ線が受かっている例が見つかっている (ATel #14834 など)
  - 新星に伴う放出物質と周囲に元からあった物質の間の衝撃波?
  - 元素合成にも影響しているかも。

- ただし、**急増光のスペクトルは殆どないので、観測例を増やしたい**
  - 新星の後期は「定常状態」近似 (e.g., Kato & Hachisu 1994) で上手くいく。
  - 初期にはこの手法も使えないので、**観測で何とかするしかない。**

新星 V1674 Her の 2 分 cadence の light curve (Quimby et al. [arXiv:2107.05763])

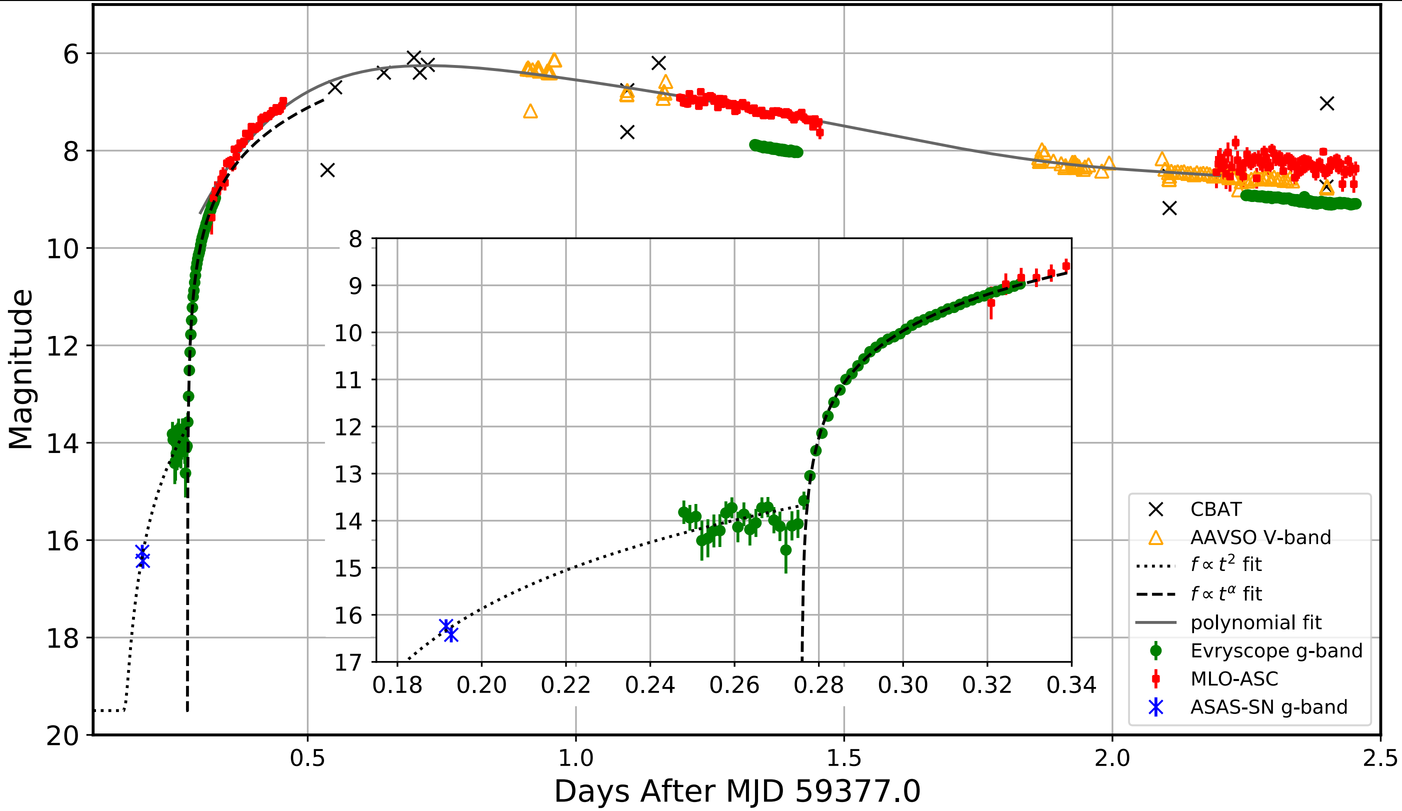
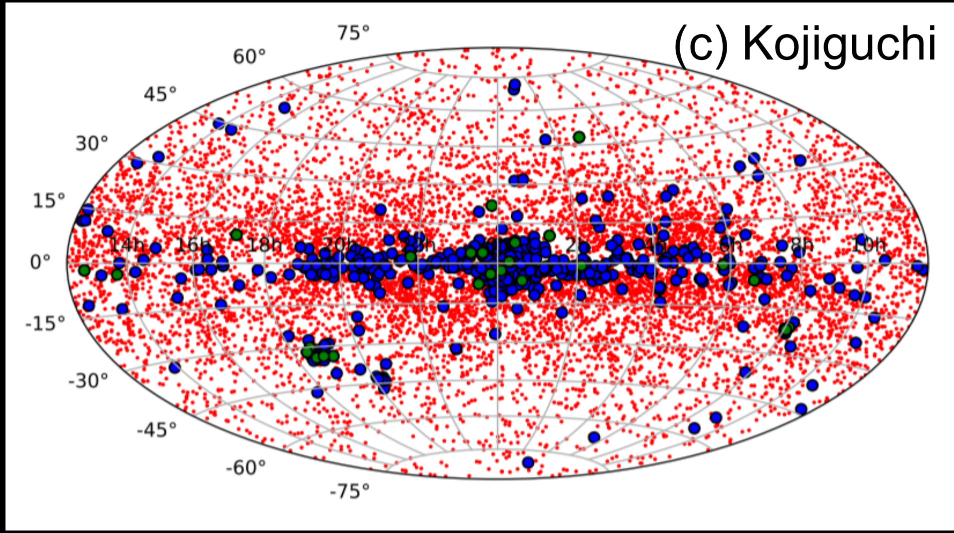


Figure 1. The complete light curve of V1674 Her based primarily on our preliminary Evryscope and ASC observations. The data have been augmented by photometric measurements from the AAVSO, CBAT and ASAS-SN. The Evryscope observations reveal pre-maximum plateau, lasting for ∼3 hr, that is highlighted in the insert. Details of the various symbols and fits to the light curve are given in the figure legend.

- 限界等級 14 等で 2 分 cadence の全天サーベイをしたら写ってた
  - 後で見返したら受かってた
    (即時に alert を出せたわけではない)
- 初期のこんなに詳細な light curve は極めて珍しい
  - スペック的には Tomo-e で可能

新星の出現位置

- **ほとんどが銀河面付近に集中**
  - 特に銀河中心が多い
  - 銀河面を高頻度でサーベイできれば、増光途上の新星が検出できるのではないか
- Event rate の見積もり
  - 日本から夜間に銀河中心が見える時間: ~ 300-400 hours / year (晴天率 1/3 くらい)
  - Nova rate ~ 10 novae / year → 1 nova / 900 hours
    (900 h 銀河中心を見れば 1 nova くらい出るはず)
  → **2-3 年頑張れば夜間の間に新星を見つけられそう**
    - Tomo-e による発見確率、も実際にはかかってくる
    - 暗い新星を含めると、もう少し上がるかも?
  - 特に、夏場はねらい目?

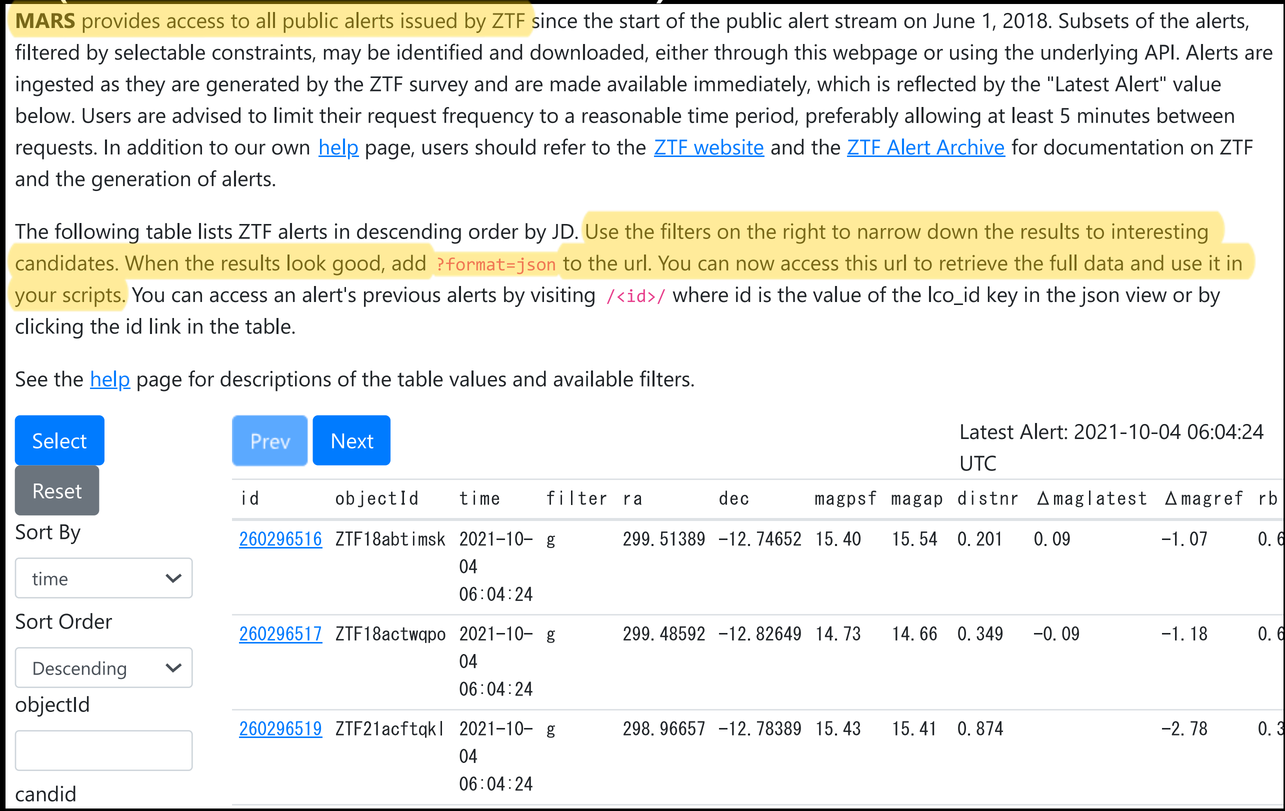


矮新星, 新星, 反復新星の
出現位置 (銀河座標)

前にちょっと趣味でやってたこと

- ZTF の全アラートにアクセスできるサイト MARS: https://mars.lco.global/
  - 等級、増光率などの条件をつけて検索が可能
  - 大量の Bogus を含むが Real/Bogus rate (ZTF 側の「自信度」) でフィルター可
  - リアルタイムで情報が上がっていく
    (2021 年末以降、まともに動いてない)

- 「2回」検出した天体等を引き出し、既知の小惑星を落とす
  - 矮新星は結構見つかる
  - 超新星もたまに (SN 2021zny など)
  - (新星はまだ無し)
- 候補は田口個人の slack で通知



MARS provides access to all public alerts issued by ZTF since the start of the public alert stream on June 1, 2018. Subsets of the alerts, filtered by selectable constraints, may be identified and downloaded, either through this webpage or using the underlying API. Alerts are ingested as they are generated by the ZTF survey and are made available immediately, which is reflected by the "Latest Alert" value below. Users are advised to limit their request frequency to a reasonable time period, preferably allowing at least 5 minutes between requests. In addition to our own help page, users should refer to the ZTF website and the ZTF Alert Archive for documentation on ZTF and the generation of alerts.

The following table lists ZTF alerts in descending order by JD. Use the filters on the right to narrow down the results to interesting candidates. When the results look good, add `?format=json` to the url. You can now access this url to retrieve the full data and use it in your scripts. You can access an alert's previous alerts by visiting /<id>/ where id is the value of the lco_id key in the json view or by clicking the id link in the table.

See the help page for descriptions of the table values and available filters.

Select

Reset

Sort By

time

Sort Order

Descending

objectId

candid

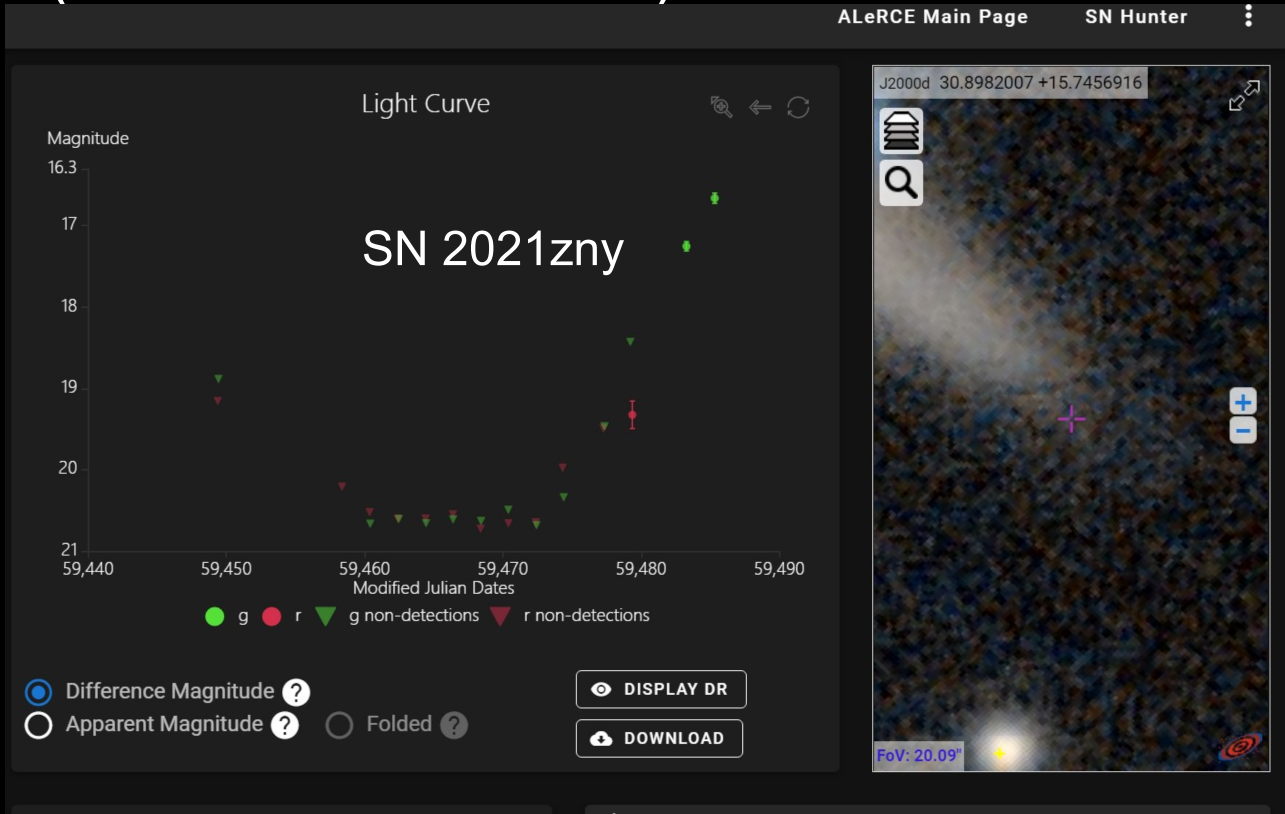
Prev Next

Latest Alert: 2021-10-04 06:04:24 UTC

id	objectId	time	filter	ra	dec	magpsf	magap	distnr	Δmaglatest	Δmagref	rb
260296516	ZTF18abtimsk	2021-10-04 06:04:24	g	299.51389	-12.74652	15.40	15.54	0.201	0.09	-1.07	0.6
260296517	ZTF18actwqpo	2021-10-04 06:04:24	g	299.48592	-12.82649	14.73	14.66	0.349	-0.09	-1.18	0.6
260296519	ZTF21acftqkl	2021-10-04 06:04:24	g	298.96657	-12.78389	15.43	15.41	0.874		-2.78	0.3

前にちょっと趣味でやってたこと

- ZTF の全アラートにアクセスできるサイト MARS: https://mars.lco.global/
  - 等級、増光率などの条件をつけて検索が可能
  - 大量の Bogus を含むが Real/Bogus rate (ZTF 側の「自信度」) でフィルター可
  - リアルタイムで情報が上がっていく
    (2021 年末以降、まともに動いてない)
- 「2回」検出した天体等を引き出し、既知の小惑星を落とす
  - 矮新星は結構見つかる
  - 超新星もたまに (SN 2021zny など)
  - (新星はまだ無し)
- 候補は田口個人の slack で通知



Tomo-e データでも (こっそり) 取り組み中

- 学校に置いてあるデスクトップからアクセス (ありがとうございます)
- 練習がてら transient 候補を全部検索。既知の矮新星などは落とす
  - 最大でも 1 日 100 個程度。人力確認も不可能じゃない。
- **データベースはかなり使いやすい**
- 効率良い hunting 法など、また相談させて下さい
- 気になっている点
  - 明るい新星だと CMOS がサチるかも
  - Non-detection も含めた増光率の計算

→ シンポジウム後にやってみる
(ある程度できたら共有したいですが)

発表時に出していた図 (Slack のスクリーンショット) は一応、消させて頂きます。

2019 年からやってきたこと + 今後の予定など

- 2019 年からの田口
  - **せいめいで下積み**
    - 京大 + 岡山の皆さまのおかげで、せいめいには少し慣れました
    - 発見直後の新星 (候補) をいち早く分光するためのプロポーザルを出し (続け) ています
  - V1405 Cas の観測結果を纏めたり (Taguchi et al., to be re-submitted)
  - 新星の超初期のスペクトルの理論的解釈の研究も進めています...

- **Tomo-e でリアルタイムで新星を発見して、同じ夜に岡山で分光できたら**、と思っています (毎回、同じこと言っていますが...)
  - 今度の 4 月からは、どこにいるのだろうか...??

- 議論に乗って頂ける方がいらっしゃいましたら、ご連絡して頂きたいです

まとめ

- 最近、**新星の爆発直後 (急増光期) が面白い**
  - **電離階数の高い line** (T Pyx: Arai et al. 2015; V1405 Cas: ATels #14471, #14472)
  - **P Cygni profile を示さないスペクトル** (Arai et al. 2015)
    - 新星爆発に伴う放出物質は光球面より十分遠方に到達しておらず、吸収成分を作れない
    - 電離光子が爆発前に存在している物質を照射している? (cf. 超新星の "flash spectroscopy")
  - 高エネルギー (> 100 MeV) ガンマ線が初期に受かる例も (RS Oph: ATel #14834 等)
    - 新星に伴う放出物質と、周囲の物質との衝突・衝撃波による放射?
  - Rising をリアルタイムで捉えた例も (Quinby et al., arXiv: [2107.05763])
    - Tomo-e でも原理的には可能

- **確率的には 2 – 3 年頑張れば出来そう**
  - どう「頑張る」か?

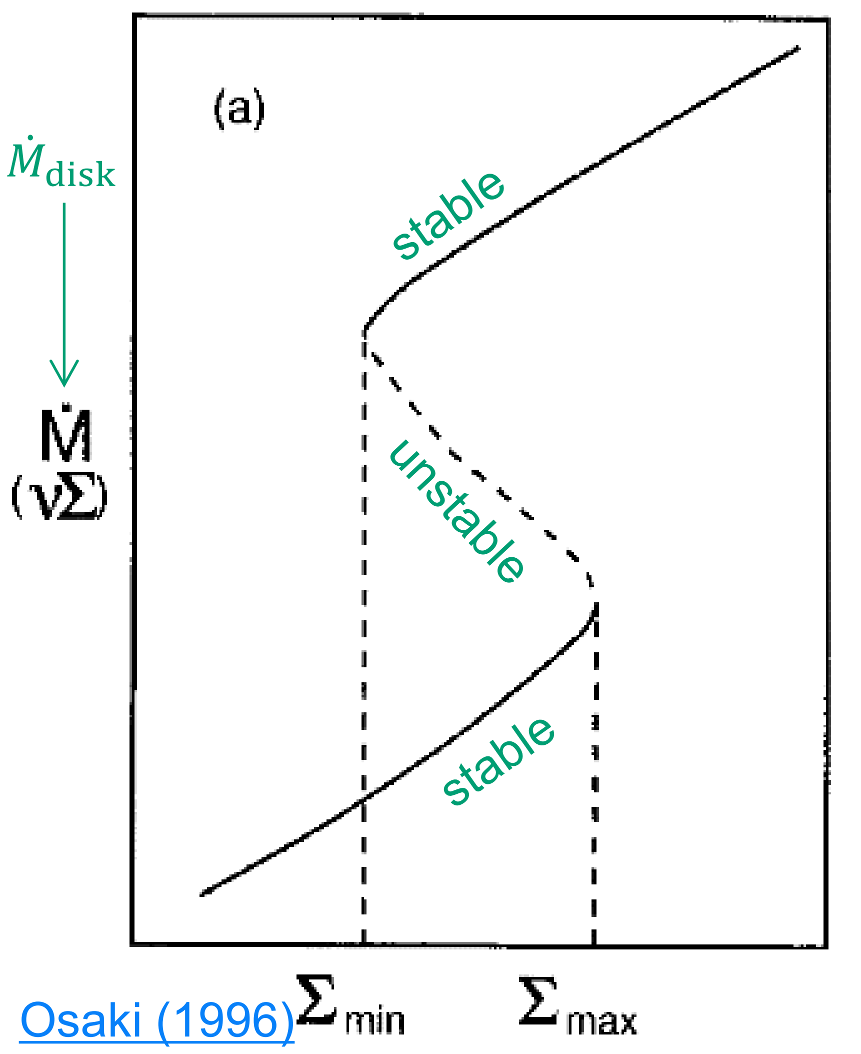
RS Ophiuchi (credit: Casey Reed)

Difference between Dwarf Novae, Novae, and Supernovae

	Dwarf Novae	Novae	Type Ia Supernovae
Causes	Instability in the disk	Thermonuclear Runaway	(Chandrasekhar?)
Energy Release	Gravitational Energy release in the disk	Nuclear Burning of Accreted Hydrogen on the WD surface	Nuclear Burning of the Entire WD
Absolute Mag	> 1 (Patterson 2011)	~ – 6 to – 10 (Bode & Evans 2008)	~ – 19
Typical Amplitude	$\lesssim$ 8	~ 10 (at least 7, at most 19)	I don't know (> 20?)
Location of Targets	MW Galaxy	MW Galaxy & nearby galaxies	Extragalactic
Discovery	~ 10^3 / year	~ 10 / year (in MW Galaxy)	~ 10^4 / year?
Recurrence	~ weeks to ~ 10^2 years	~ 1 year to ~ 10^4 years?	One-off

Dwarf Novae and Novalike Variables (Novalikes)

- Thermal-equilibrium curve for $\dot{M}_{\rm disk}$ is S-shaped.
  - Solid line: Stable, Dashed line: Unstable
- Dwarf Novae
  - $\dot{M}_{\rm in}$ (inflow from secondary) is unstable for the disk.
    → $\dot{M}_{\rm disk}$ varies dramatically
      - A → B: $\dot{M}_{\rm disk} < \dot{M}_{\rm in} \rightarrow \Sigma \nearrow$, C → D: $\dot{M}_{\rm disk} > \dot{M}_{\rm in} \rightarrow \Sigma \searrow$
      - In average, $\langle \dot{M}_{\rm disk} \rangle = \dot{M}_{\rm in}$
- Novalikes
  - The input $\dot{M}_{\rm in}$ is in the stable region.
    → No DN outbursts (always hot, $\dot{M}_{\rm disk} = \dot{M}_{\rm in}$).
  - Novalike's spectra are like those of quiescent novae.
    (That's why they are called "novalikes")



Osaki (1996)

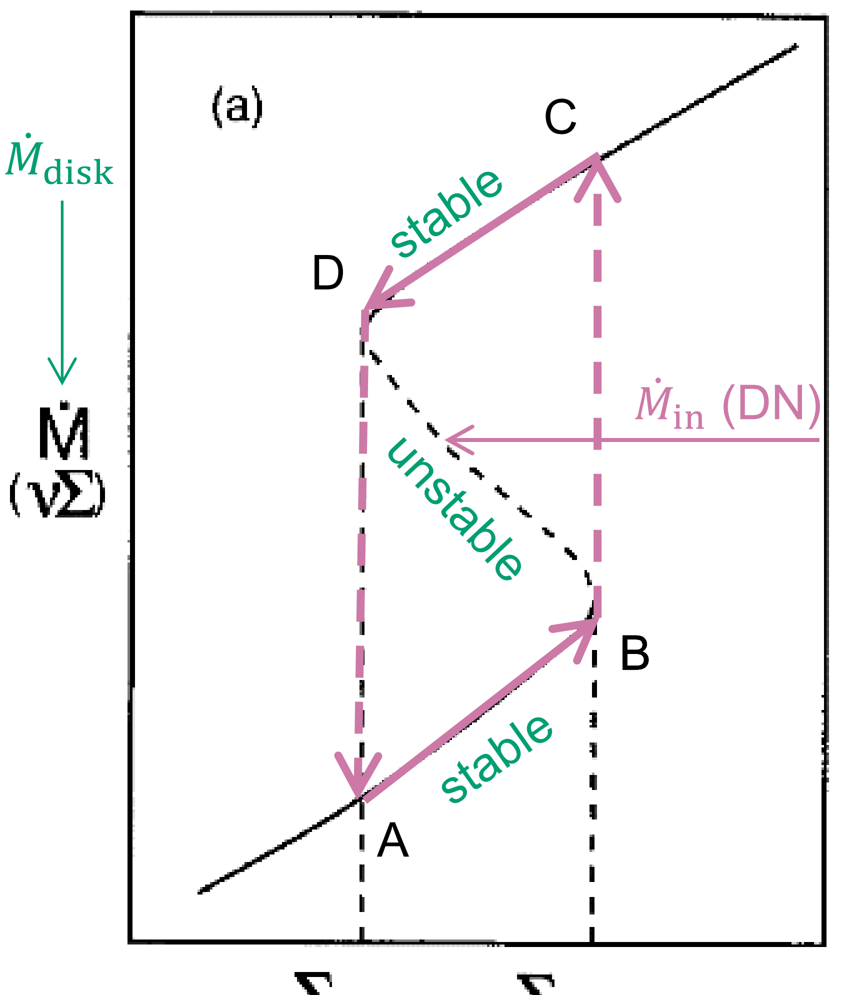
Dwarf Novae and Novalike Variables (Novalikes)

- Thermal-equilibrium curve for $\dot{M}_{\rm disk}$ is S-shaped.
  - Solid line: Stable, Dashed line: Unstable
- Dwarf Novae
  - $\dot{M}_{\rm in}$ (inflow from secondary) is unstable for the disk.

    → $\dot{M}_{\rm disk}$ varies dramatically
    - A → B: $\dot{M}_{\rm disk} < \dot{M}_{\rm in} \rightarrow \Sigma \nearrow$, C → D: $\dot{M}_{\rm disk} > \dot{M}_{\rm in} \rightarrow \Sigma \searrow$
    - In average, $\langle \dot{M}_{\rm disk} \rangle = \dot{M}_{\rm in}$
- Novalikes
  - The input $\dot{M}_{\rm in}$ is in the stable region.

    → No DN outbursts (always hot, $\dot{M}_{\rm disk} = \dot{M}_{\rm in}$).
  - Novalike's spectra are like those of quiescent novae.

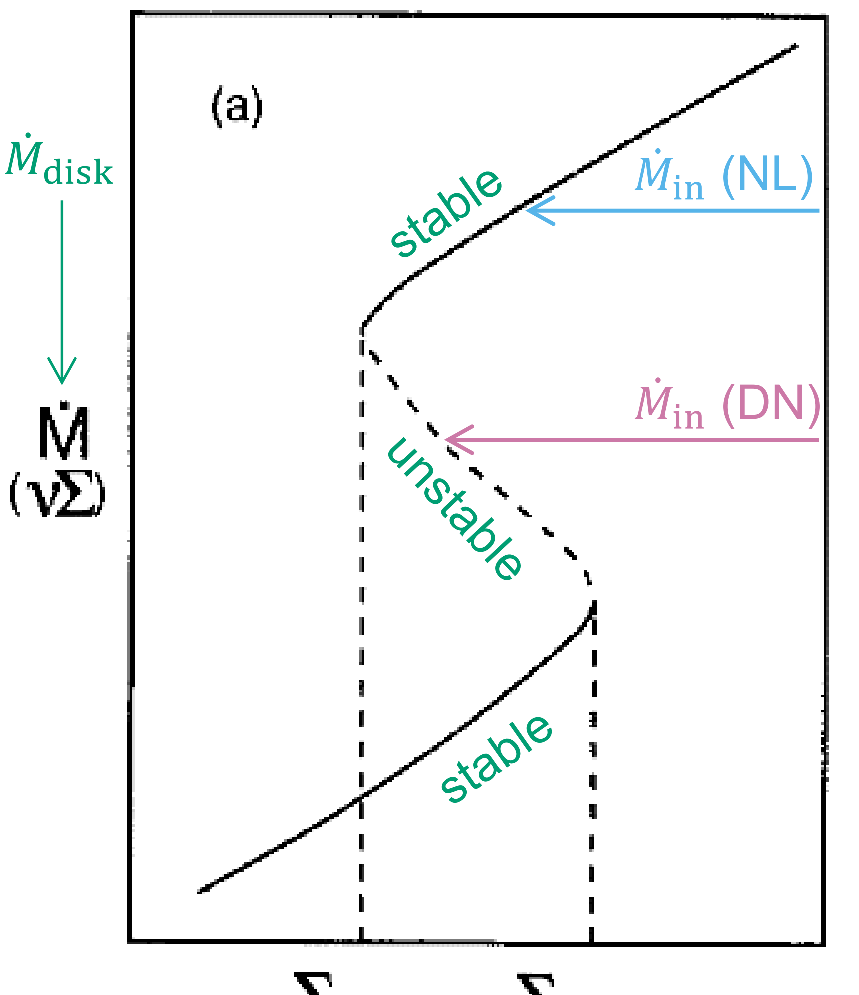
    (That's why they are called "novalikes")



Osaki (1996)

Dwarf Novae and Novalike Variables (Novalikes)

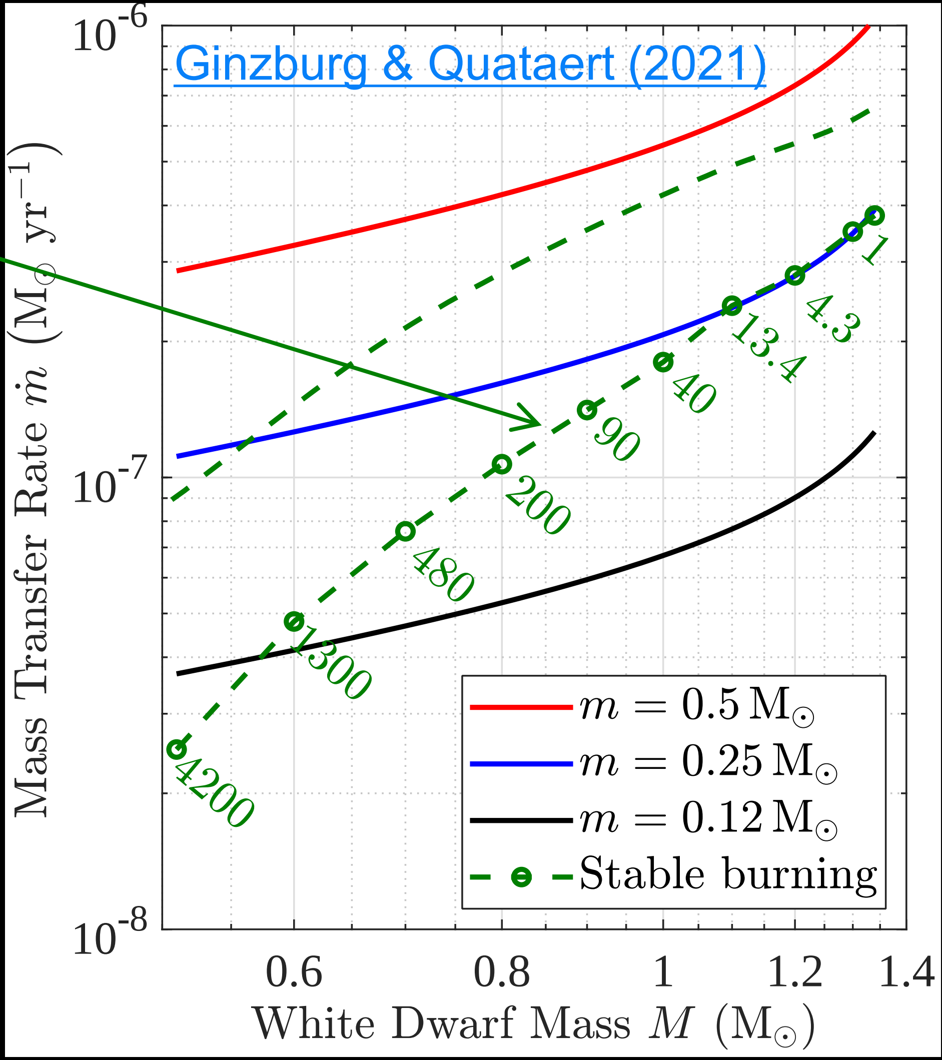
- Thermal-equilibrium curve for $\dot{M}_{\rm disk}$ is S-shaped.
  - Solid line: Stable, Dashed line: Unstable
- Dwarf Novae
  - $\dot{M}_{\rm in}$ (inflow from secondary) is unstable for the disk.
    → $\dot{M}_{\rm disk}$ varies dramatically
    - A → B: $\dot{M}_{\rm disk} < \dot{M}_{\rm in} \rightarrow \Sigma \nearrow$, C → D: $\dot{M}_{\rm disk} > \dot{M}_{\rm in} \rightarrow \Sigma \searrow$
    - In average, $\langle \dot{M}_{\rm disk} \rangle = \dot{M}_{\rm in}$
- Novalikes
  - The input $\dot{M}_{\rm in}$ is in the stable region.
    → No DN outbursts (always hot, $\dot{M}_{\rm disk} = \dot{M}_{\rm in}$).
  - Novalike's spectra are like those of quiescent novae.
    (That's why they are called "novalikes")



Osaki (1996)

Super-soft Sources and “Born-Again Giant”

- If the accretion onto WD ($\dot{M}$) is high enough, the H burning occurs continuously.
  - Rather than episodically (novae).
  - Observed as a supersoft X-ray source (SSS).
- If $\dot{M}$ was further increased, the inflow material could not be assimilated simultaneously.
  → “Born-again giant”.
- If $\dot{M}$ is low enough, H can’t be burnt steadily.
  → Ignition after enough fuel has accreted (novae).

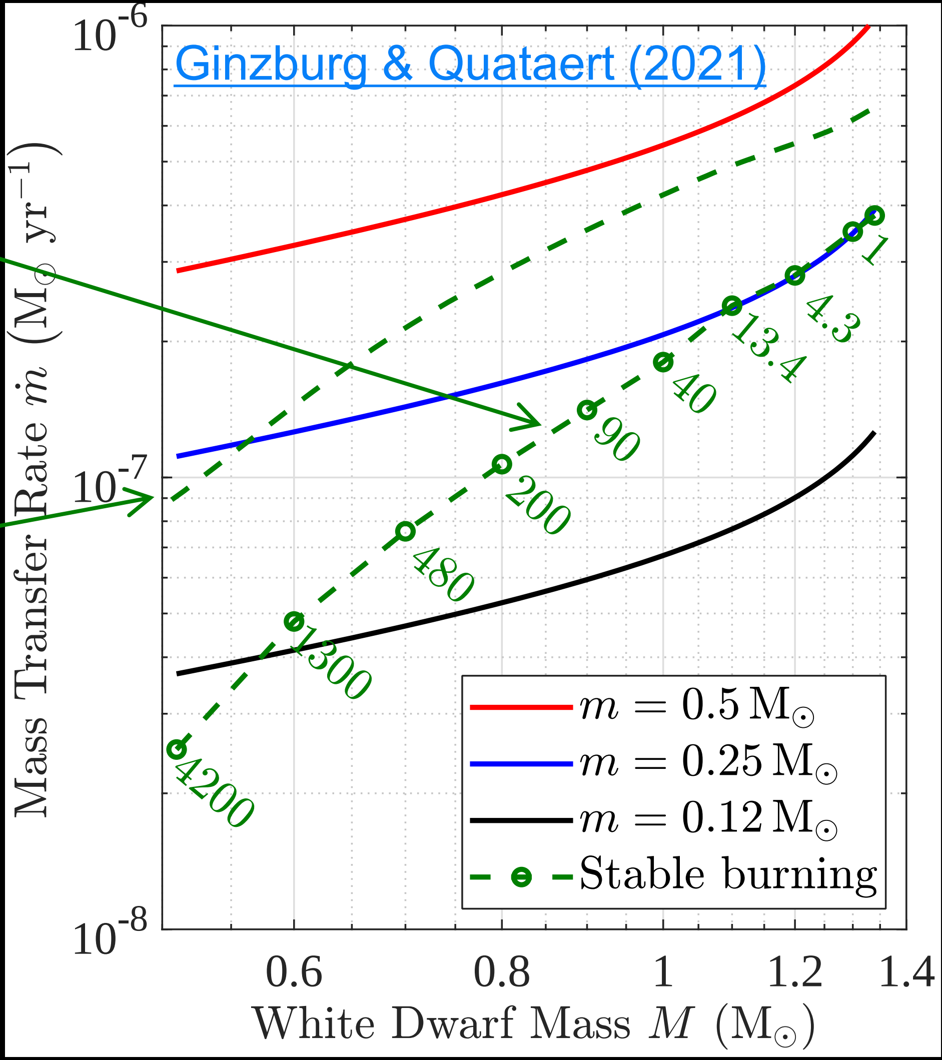


Super-soft Sources and “Born-Again Giant”

- If the accretion onto WD ($\dot{M}$) is high enough, the H burning occurs continuously.
  - Rather than episodically (novae).
  - Observed as a supersoft X-ray source (SSS).

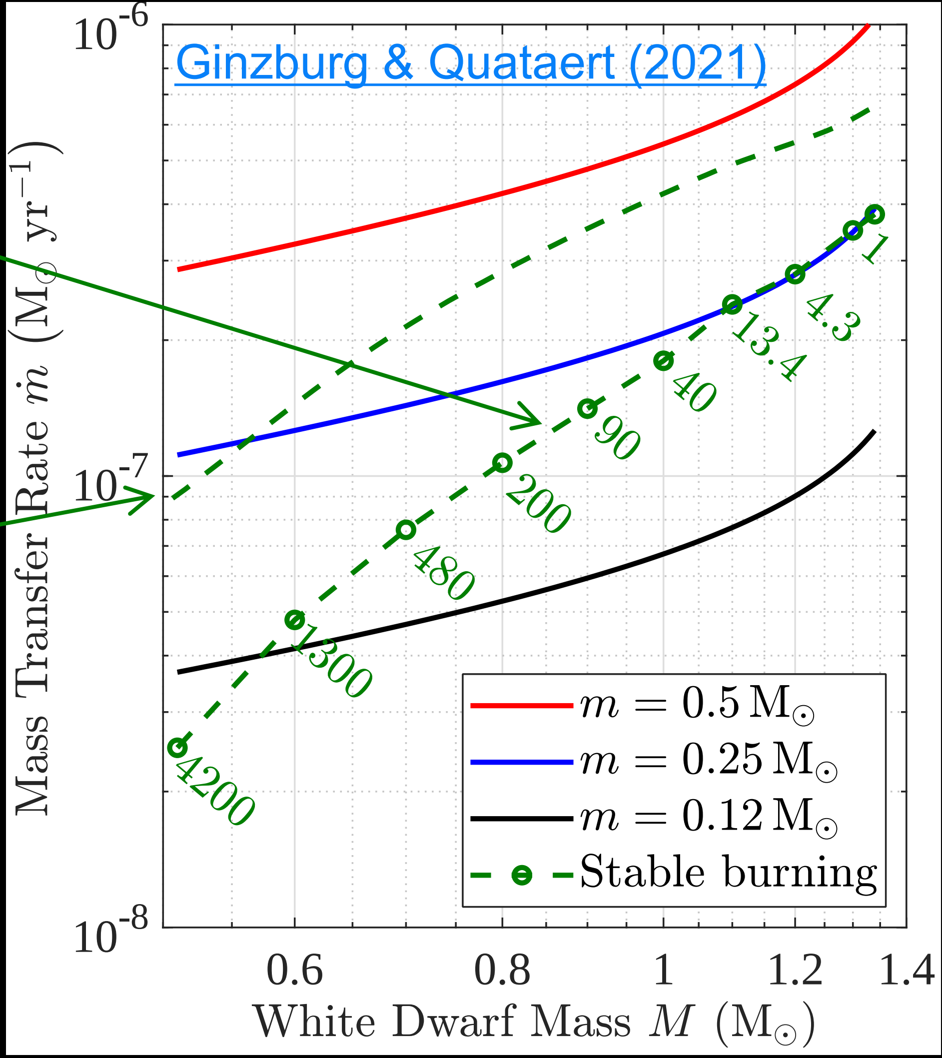
- If $\dot{M}$ was further increased, the inflow material could not be assimilated simultaneously.
  → “Born-again giant”.

- If $\dot{M}$ is low enough, H can’t be burnt steadily.
  → Ignition after enough fuel has accreted (novae).



Super-soft Sources and “Born-Again Giant”

- If the accretion onto WD ($\dot{M}$) is high enough, the H burning occurs continuously.
  - Rather than episodically (novae).
  - Observed as a supersoft X-ray source (SSS).
- If $\dot{M}$ was further increased, the inflow material could not be assimilated simultaneously.
  → “Born-again giant”.
- If $\dot{M}$ is low enough, H can’t be burnt steadily.
  → Ignition after enough fuel has accreted (novae).



Appendix: Secular Stability of Stellar Core

- Hydrostatic equilibrium
  - Pressure balance: $\frac{\mathrm{d}P}{\mathrm{d}r} = -\rho \frac{Gm}{r^2}$
  - Equation of continuity: $\frac{\mathrm{d}m}{\mathrm{d}r} = 4\pi r^2 \rho$
  - Polytropic EoS: $P = K\rho^{1+1/n}$

$\rightarrow P_\mathrm{c} = (4\pi)^{1/3} B_n G M^{2/3} \rho_\mathrm{c}^{4/3}$ (R eliminated) $\rightarrow \frac{\mathrm{d}P_\mathrm{c}}{P_\mathrm{c}} = \frac{4}{3}\frac{\mathrm{d}\rho_\mathrm{c}}{\rho_\mathrm{c}}$

- EoS: $\frac{\mathrm{d}P_\mathrm{c}}{P_\mathrm{c}} = a\frac{\mathrm{d}\rho_\mathrm{c}}{\rho_\mathrm{c}} + b\frac{\mathrm{d}T_\mathrm{c}}{T_\mathrm{c}}$ ($a = b = 1$ for ideal gas)

$\rightarrow \left(\frac{4}{3} - a\right)\frac{\mathrm{d}\rho_\mathrm{c}}{\rho_\mathrm{c}} = b\frac{\mathrm{d}T_\mathrm{c}}{T_\mathrm{c}}$

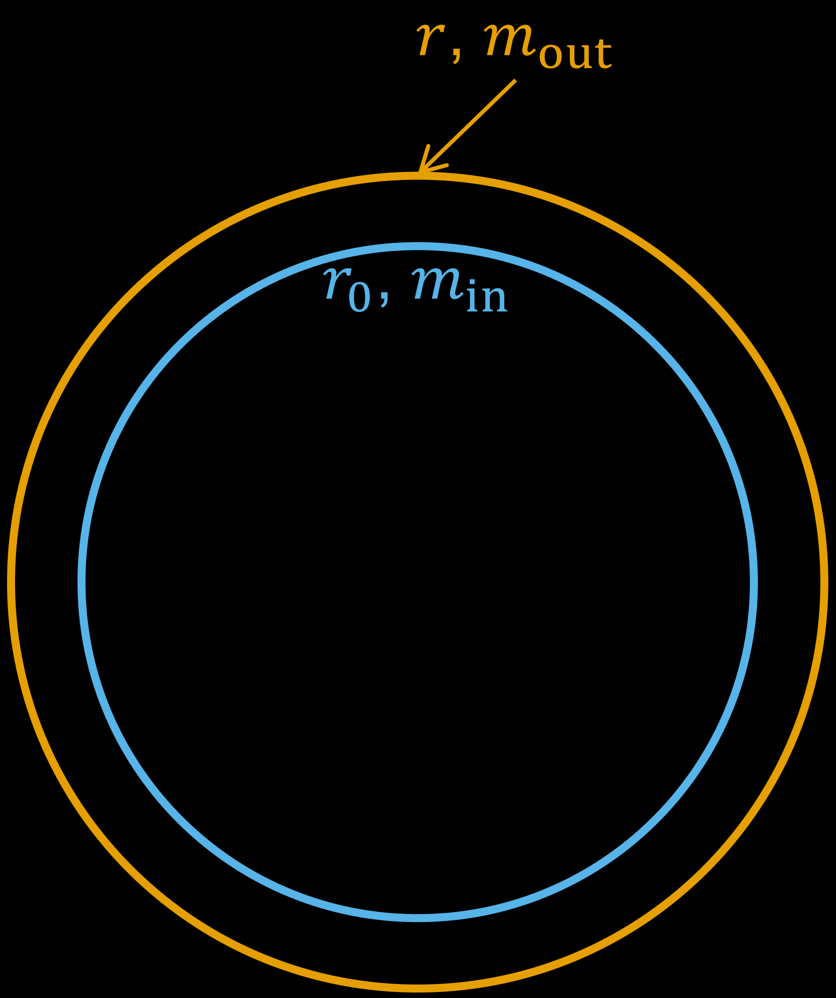
- For ideal gas, the core is secular stable.
  - T_c ↗ → nuclear energy ↗ → energy excess → expansion (ρ_c ↘) → T_c ↘

Consideration of Stability of Thin Shell (1)
(c.f. "Pulse instability" in AGB stars: e.g., Schwarzschild & Härm 1965)

- Consider a thin shell between r_0 and r.
  - Since $\mathrm{d}P = -\frac{Gm}{4\pi r^4}\mathrm{d}m$, the pressure difference is
    - $P(r) - P(r_0) \approx -\frac{Gm_{\mathrm{out}}^2}{4\pi r^4} + \frac{Gm_{\mathrm{in}}^2}{4\pi r_0^4}$.
- If there's an energy excess (only) in the shell,
  - Outer boundary will expand ($r \to r + \mathrm{d}r$).
  - The pressure difference will be
    - $\tilde{P}(r+\mathrm{d}r) - P(r_0) \approx -\frac{Gm_{\mathrm{out}}^2}{4\pi(r+\mathrm{d}r)^4} + \frac{Gm_{\mathrm{in}}^2}{4\pi r_0^4}$.
- So, the pressure at outer boundary follows

$$\mathrm{d}P = \tilde{P}(r+\mathrm{d}r) - P(r) \approx -\frac{Gm_{\mathrm{out}}^2}{4\pi}\left(\frac{1}{(r+\mathrm{d}r)^4} - \frac{1}{r^4}\right)$$

  - This means $\frac{\mathrm{d}P}{P} = -4\frac{\mathrm{d}r}{r}$.



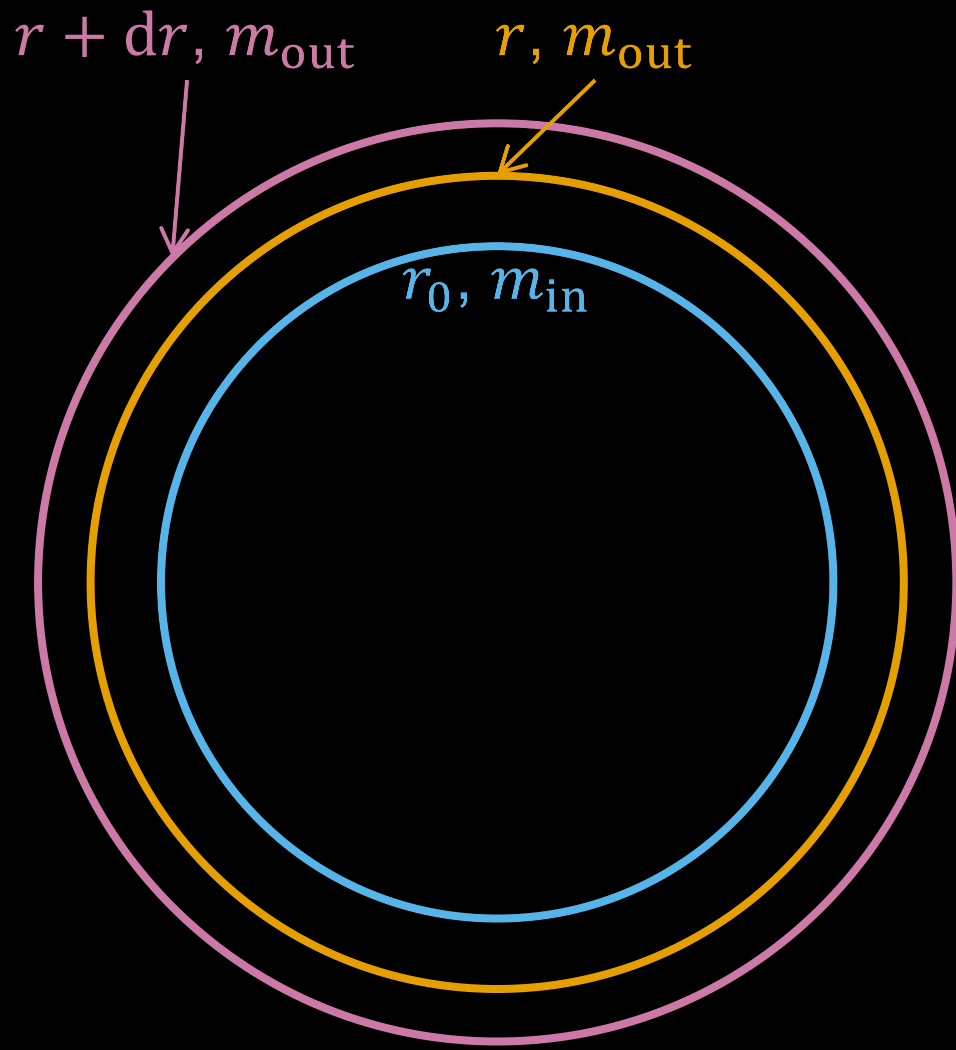
Consideration of Stability of Thin Shell (1)

(c.f. "Pulse instability" in AGB stars: e.g., Schwarzschild & Härm 1965)

- Consider a thin shell between r_0 and r.
  - Since $\mathrm{d}P = -\frac{Gm}{4\pi r^4}\mathrm{d}m$, the pressure difference is
    - $P(r) - P(r_0) \approx -\frac{Gm_{\mathrm{out}}^2}{4\pi r^4} + \frac{Gm_{\mathrm{in}}^2}{4\pi r_0^4}$.
- If there's an energy excess (only) in the shell,
  - Outer boundary will expand ($r \to r + \mathrm{d}r$).
  - The pressure difference will be
    - $\tilde{P}(r+\mathrm{d}r) - P(r_0) \approx -\frac{Gm_{\mathrm{out}}^2}{4\pi (r+\mathrm{d}r)^4} + \frac{Gm_{\mathrm{in}}^2}{4\pi r_0^4}$.
- So, the pressure at outer boundary follows

$$\mathrm{d}P = \tilde{P}(r+\mathrm{d}r) - P(r) \approx -\frac{Gm_{\mathrm{out}}^2}{4\pi}\left(\frac{1}{(r+\mathrm{d}r)^4} - \frac{1}{r^4}\right)$$

  - This means $\frac{\mathrm{d}P}{P} = -4\frac{\mathrm{d}r}{r}$.



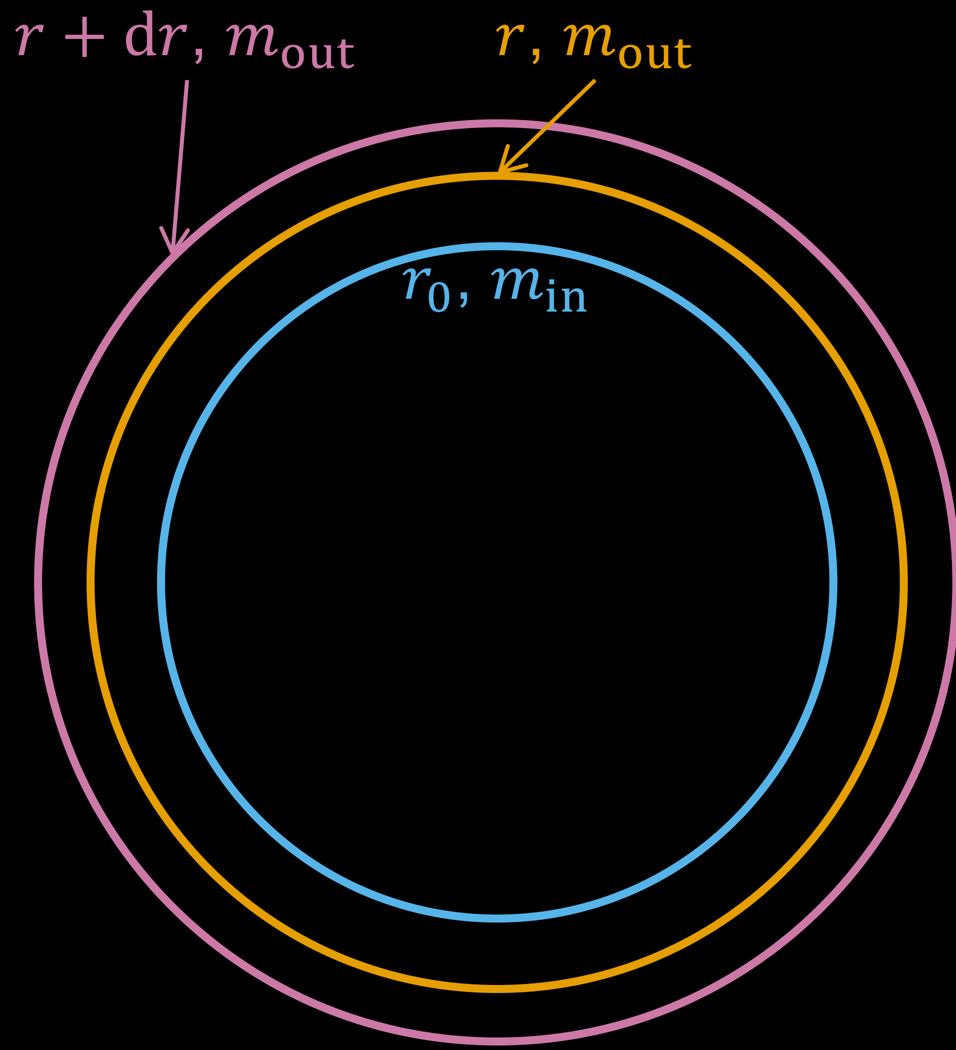
Consideration of Stability of Thin Shell (1)

(c.f. "Pulse instability" in AGB stars: e.g., Schwarzschild & Härm 1965)

- Consider a thin shell between r_0 and r.
  - Since $\mathrm{d}P = -\frac{Gm}{4\pi r^4}\mathrm{d}m$, the pressure difference is
    - $P(r) - P(r_0) \approx -\frac{Gm_{\mathrm{out}}^2}{4\pi r^4} + \frac{Gm_{\mathrm{in}}^2}{4\pi r_0^4}$.
- If there's an energy excess (only) in the shell,
  - Outer boundary will expand ($r \to r + \mathrm{d}r$).
  - The pressure difference will be
    - $\tilde{P}(r + \mathrm{d}r) - P(r_0) \approx -\frac{Gm_{\mathrm{out}}^2}{4\pi (r+\mathrm{d}r)^4} + \frac{Gm_{\mathrm{in}}^2}{4\pi r_0^4}$.
- So, the pressure at outer boundary follows

$$\mathrm{d}P = \tilde{P}(r + \mathrm{d}r) - P(r) \approx -\frac{Gm_{\mathrm{out}}^2}{4\pi}\left(\frac{1}{(r+\mathrm{d}r)^4} - \frac{1}{r^4}\right)$$

  - This means $\frac{\mathrm{d}P}{P} = -4\frac{\mathrm{d}r}{r}$.



Consideration of Stability of Thin Shell (2)

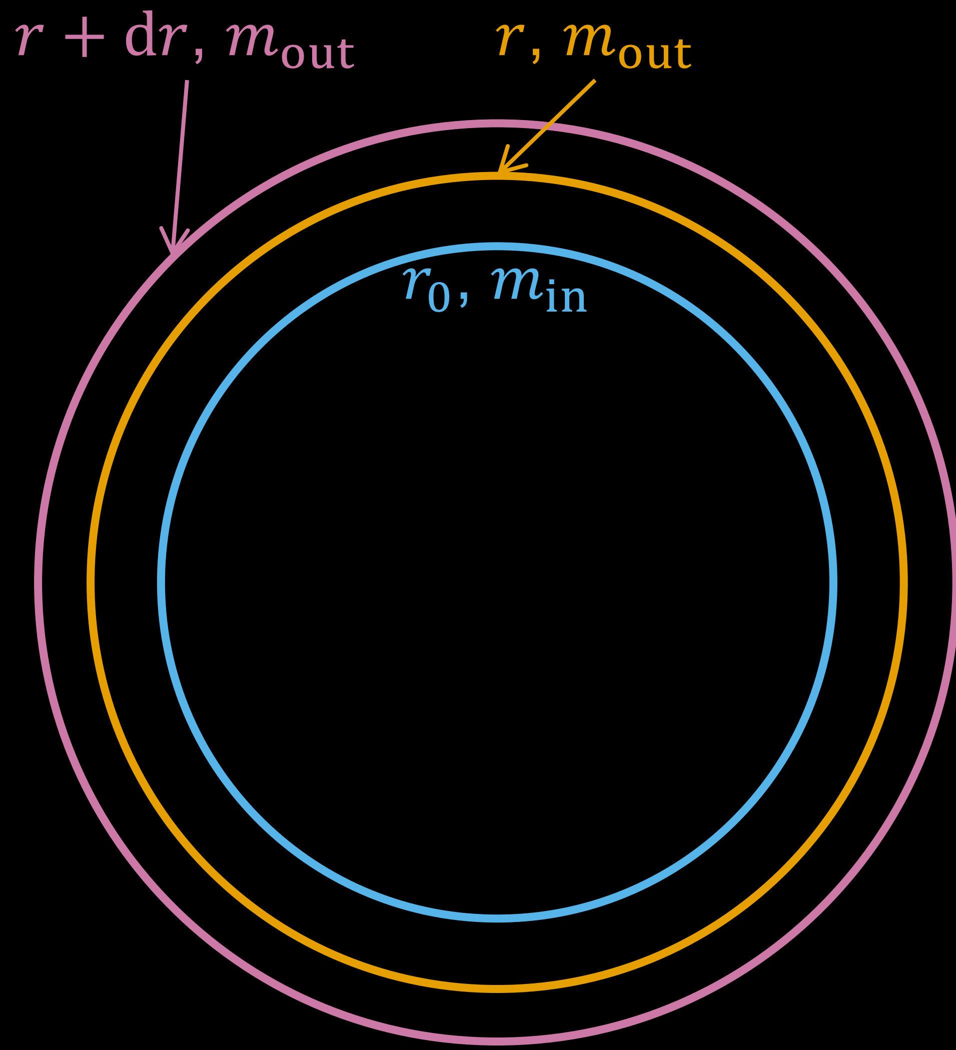
(c.f. "Pulse instability" in AGB stars: e.g., Schwarzschild & Härm 1965)

- From the previous slide, $\frac{\mathrm{d}P}{P} = -4\frac{\mathrm{d}r}{r}$
- The shell mass Δm doesn't change.
  - $\Delta m \approx 4\pi r_0^2 \rho(r_0)(r - r_0)$: constant

  $\rightarrow \frac{\mathrm{d}\rho}{\rho} = -\frac{\mathrm{d}r}{r - r_0}$
- EoS: $\frac{\mathrm{d}P}{P} = a\frac{\mathrm{d}\rho}{\rho} + b\frac{\mathrm{d}T}{T}$ ($a = b = 1$: ideal gas)

$\rightarrow \left(\frac{4(r-r_0)}{r} - a\right)\frac{\mathrm{d}\rho_\mathrm{c}}{\rho_\mathrm{c}} = b\frac{\mathrm{d}T_\mathrm{c}}{T_\mathrm{c}}$

  - The point is $(r - r_0)/r$ is usually very small.
- $T \nearrow$ → nuclear energy $\nearrow$ → energy excess → expansion ($\rho \searrow$) → $T \nearrow$



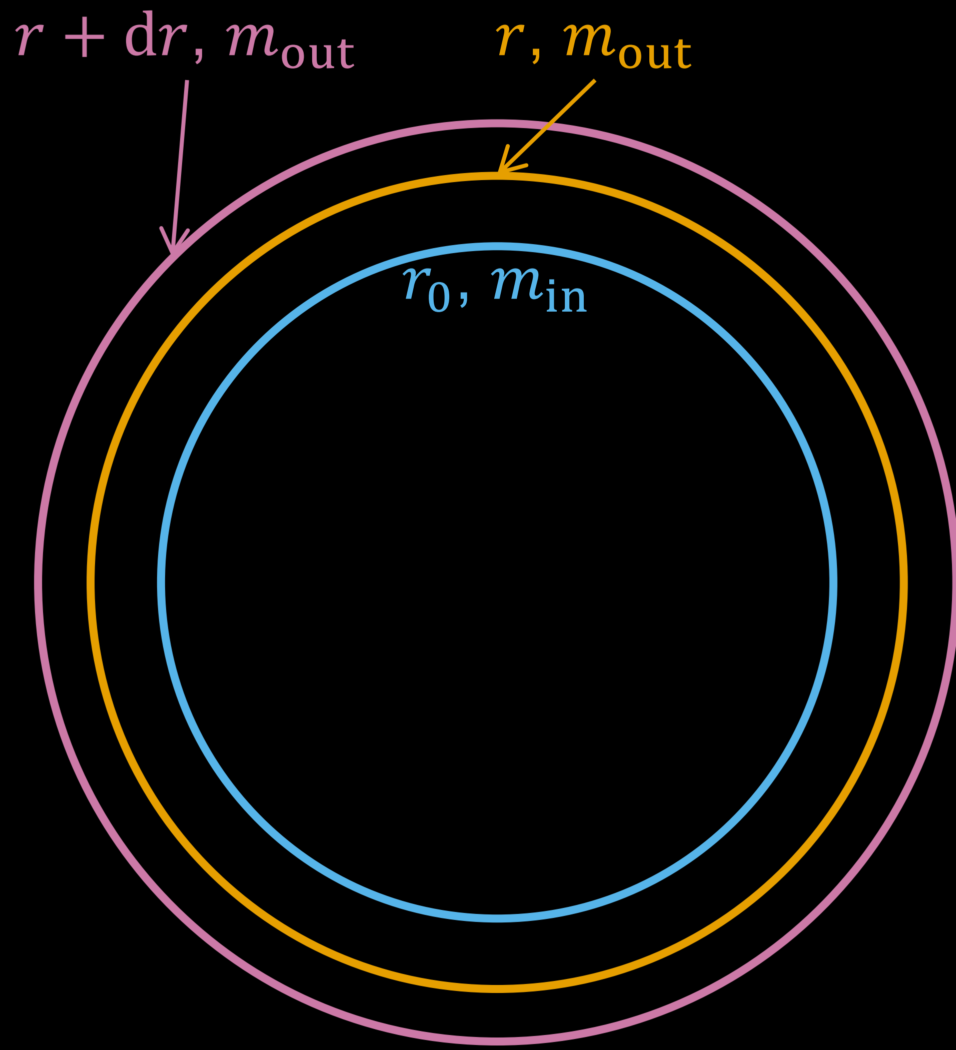
Consideration of Stability of Thin Shell (2)

(c.f. "Pulse instability" in AGB stars: e.g., Schwarzschild & Härm 1965)

- From the previous slide, $\frac{\mathrm{d}P}{P} = -4\frac{\mathrm{d}r}{r}$
- The shell mass Δm doesn't change.
  - $\Delta m \approx 4\pi r_0^2 \rho(r_0)(r - r_0)$: constant

  $\rightarrow \frac{\mathrm{d}\rho}{\rho} = -\frac{\mathrm{d}r}{r-r_0}$
- EoS: $\frac{\mathrm{d}P}{P} = a\frac{\mathrm{d}\rho}{\rho} + b\frac{\mathrm{d}T}{T}$ ($a = b = 1$: ideal gas)

$\rightarrow \left(\frac{4(r-r_0)}{r} - a\right)\frac{\mathrm{d}\rho_\mathrm{c}}{\rho_\mathrm{c}} = b\frac{\mathrm{d}T_\mathrm{c}}{T_\mathrm{c}}$
  - The point is $(r - r_0)/r$ is usually very small.
- $T \nearrow$ → nuclear energy $\nearrow$ → energy excess → expansion ($\rho \searrow$) → $T \nearrow$



Consideration of Stability of Thin Shell (2)

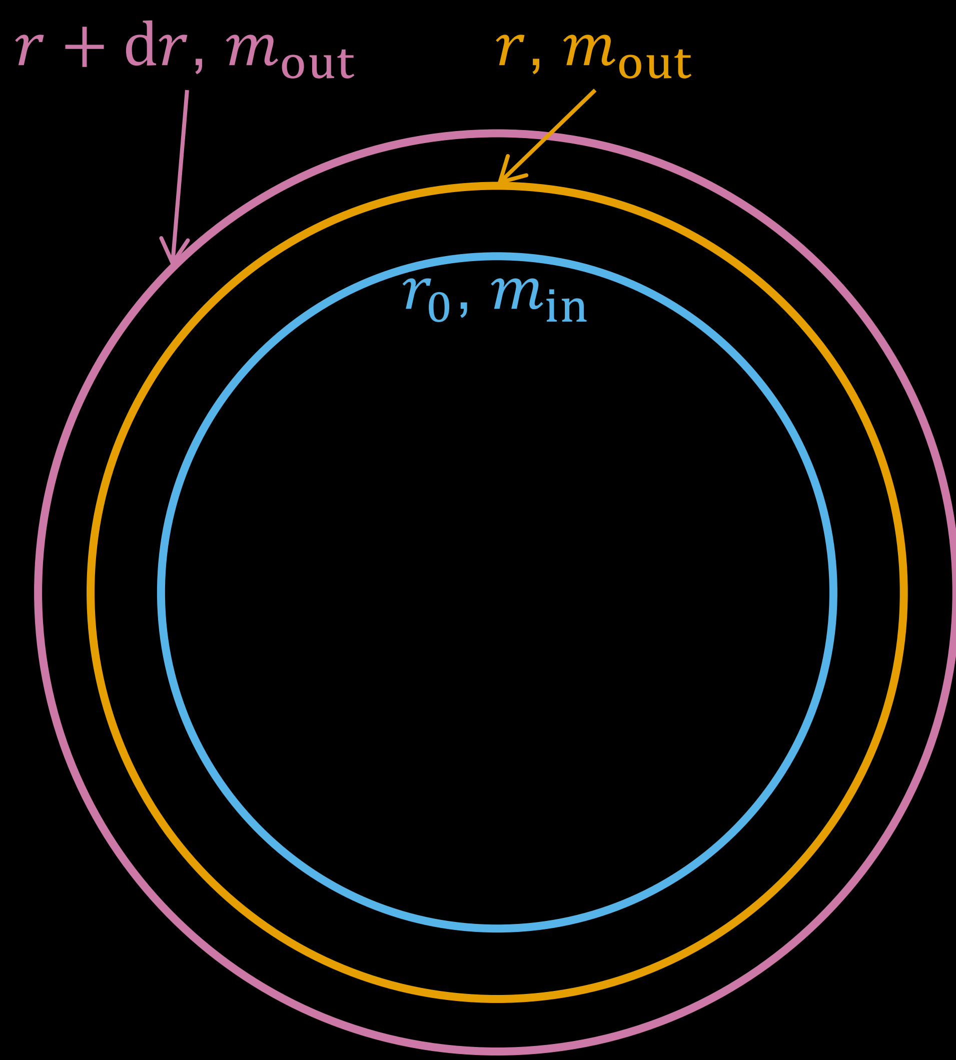
(c.f. "Pulse instability" in AGB stars: e.g., Schwarzschild & Härm 1965)

- From the previous slide, $\frac{\mathrm{d}P}{P} = -4\frac{\mathrm{d}r}{r}$
- The shell mass Δm doesn't change.
  - $\Delta m \approx 4\pi r_0^2 \rho(r_0)(r - r_0)$: constant

  $\rightarrow \frac{\mathrm{d}\rho}{\rho} = -\frac{\mathrm{d}r}{r - r_0}$
- EoS: $\frac{\mathrm{d}P}{P} = a\frac{\mathrm{d}\rho}{\rho} + b\frac{\mathrm{d}T}{T}$ ($a = b = 1$: ideal gas)

$\rightarrow \left(\frac{4(r-r_0)}{r} - a\right)\frac{\mathrm{d}\rho_\mathrm{c}}{\rho_\mathrm{c}} = b\frac{\mathrm{d}T_\mathrm{c}}{T_\mathrm{c}}$

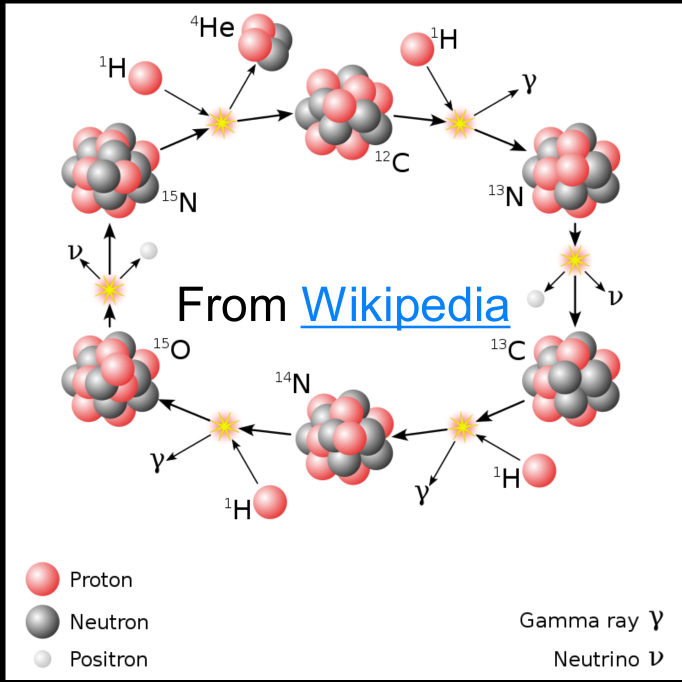
  - The point is $(r - r_0)/r$ is usually very small.
- T ↗ → nuclear energy ↗ → energy excess → expansion (ρ ↘) → T ↗



Thermonuclear Runaway (TNR) (e.g. Starrfield et al. 2016)

- Nuclear reaction first starts from the p-p chain.
  - pep reaction ($p + e^- + p \rightarrow d + \nu$) is included (Starrfield et al. 2009)
  - Degeneracy becomes unimportant at $\sim 7 \times 10^7$ K, but TNR can't be terminated.
- Ultimately, hot CNO cycle power final stages of TNR.
  - At high temperatures ($> 10^8$ K), protons are captured so fast.
    $\rightarrow$ the rate of energy generation is limited by $\tau_{1/2}$ of β^+-decay.
    (^{13}N: 598 s, ^{14}O: 71 s, ^{15}O: 122 s, ^{17}F: 64 s)
    - In usual stars, the bottle neck is $^{14}N + p \rightarrow {}^{15}O + \gamma$.
  - Convective turnover timescale: $10\text{-}10^2$ s
    $\rightarrow$ β^+-radiative nuclei are transported for the whole H-rich envelope.

(However, I feel the detail of TNR is still under debates.)



Energetics of Novae (1)

- Where does the Nuclear Luminosity L_{nuc} Go?
  - Radiated away (L_{ph})
  - Expands envelope
    - Mostly used for Gravitational energy loss ($L_G < 0$)
    - Internal Energy (for later use)
  - Essensially, $L_{nuc} – (–L_G) = L_{ph}$

- Eddington Luminosity (next slide) plays a very important role in energetics.

Energetics of Novae (1)

- Where does the Nuclear Luminosity L_{nuc} Go?
  - Radiated away (L_{ph})
  - Expands envelope
    - Mostly used for Gravitational energy loss ($L_G < 0$)
    - Internal Energy (for later use)
  - Essensially, $L_{nuc} - (-L_G) = L_{ph}$

- Eddington Luminosity (next slide) plays a very important role in energetics.

Energetics of Novae (2): Eddington Luminosity

- An upper limit of the luminosity of stars in hydrostatic equilibrium.
- Classically defined as
  $L_{\mathrm{Edd}} = \frac{4\pi cGM}{\kappa_{\mathrm{es}}}$ (κ_{es}: opacity by electron scattering)
  - Gravity ~ $\frac{GM\rho}{r^2}$
  - Radiative force ~ $\frac{L}{4\pi r^2 h\nu} \frac{h\nu}{c} \kappa\rho \sim \frac{\kappa\rho L}{4\pi c r^2}$
    - $\frac{L}{4\pi r^2 h\nu}$: photon number flux
    - $\frac{h\nu}{c}$: momentum of photon
    - $\kappa\rho$: absorption coefficient
- If diffusive luminosity > L_{Edd}, envelope can't be in hydrostatic equilibrium.
  → (A part of) the envelope is ejected.

Energetics of Novae (3)

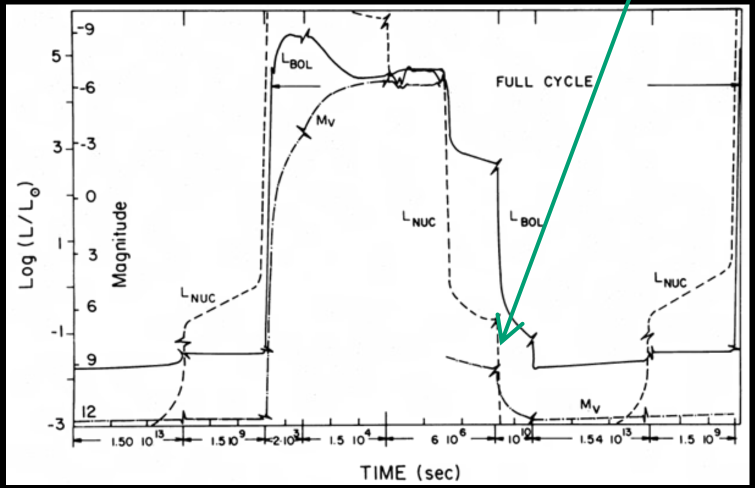
- In the first nuclear flash, L_{nuc} largely exceeds L_{Edd}.
  - Most of L_{nuc} is spent on L_G.

  → As a result, the envelope is expanded.

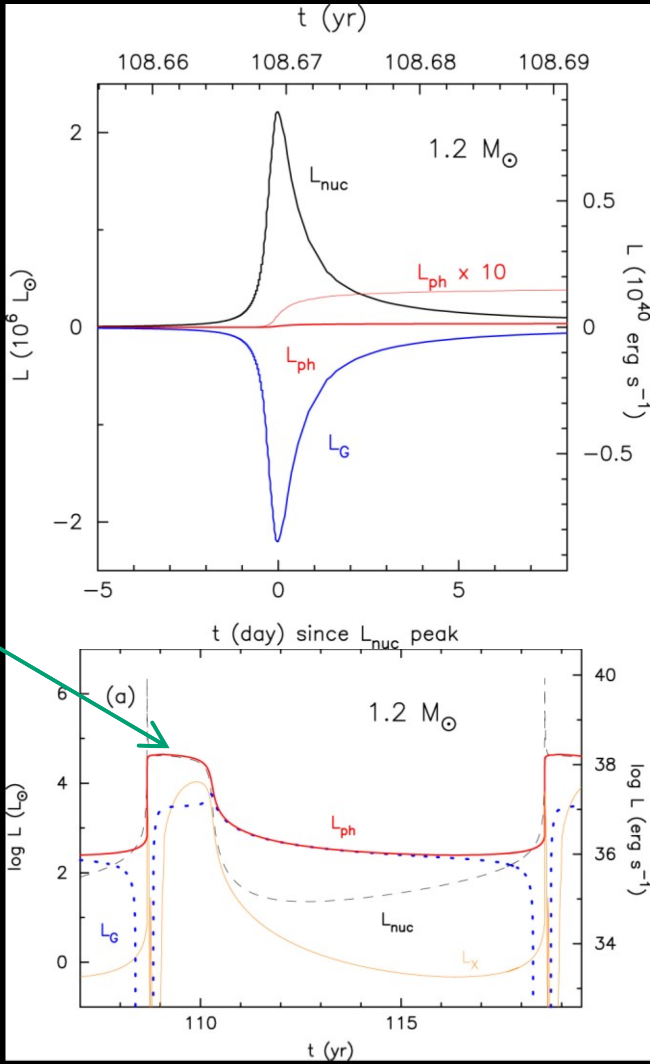
  → Then ρ decreases → L_{nuc} gets mild.

  → Gradually L_{nuc} settle in L_{Edd} : (Quasi) Steady State
  - H-burning is unsustainable due to depletion.

  → Finally burning ends, and WD returns to the quiescent.



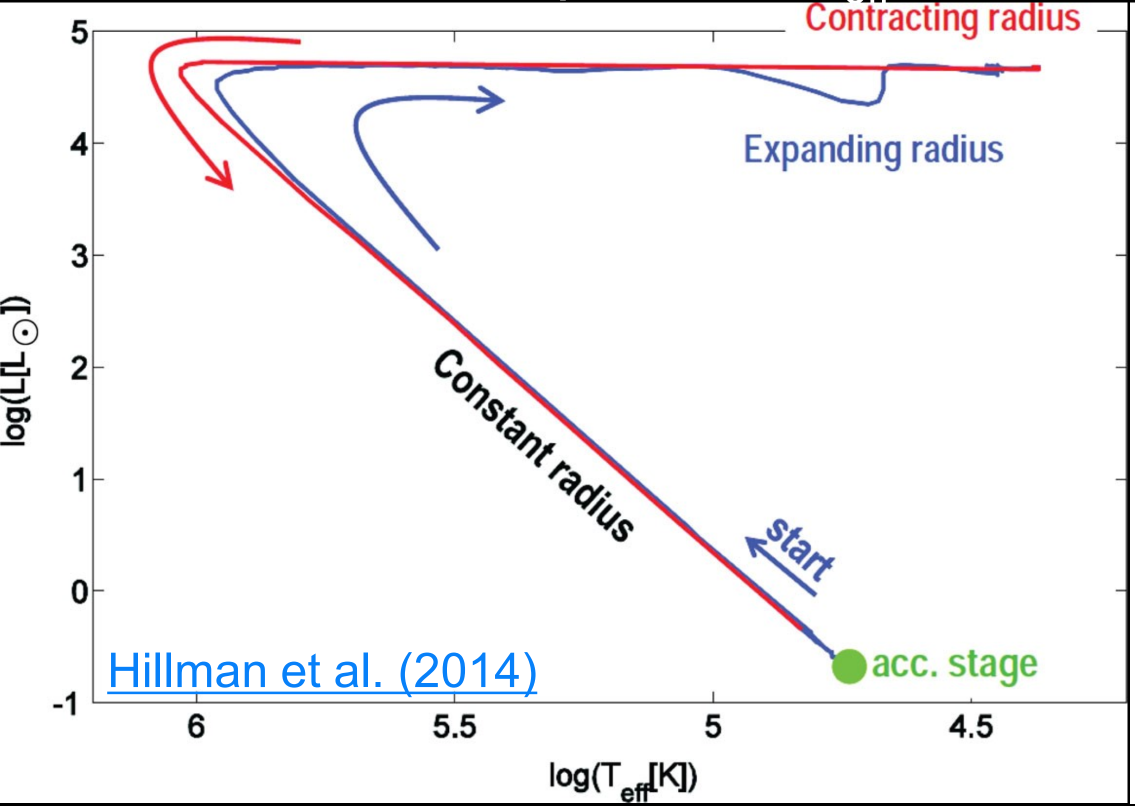
Prialnik (1986)

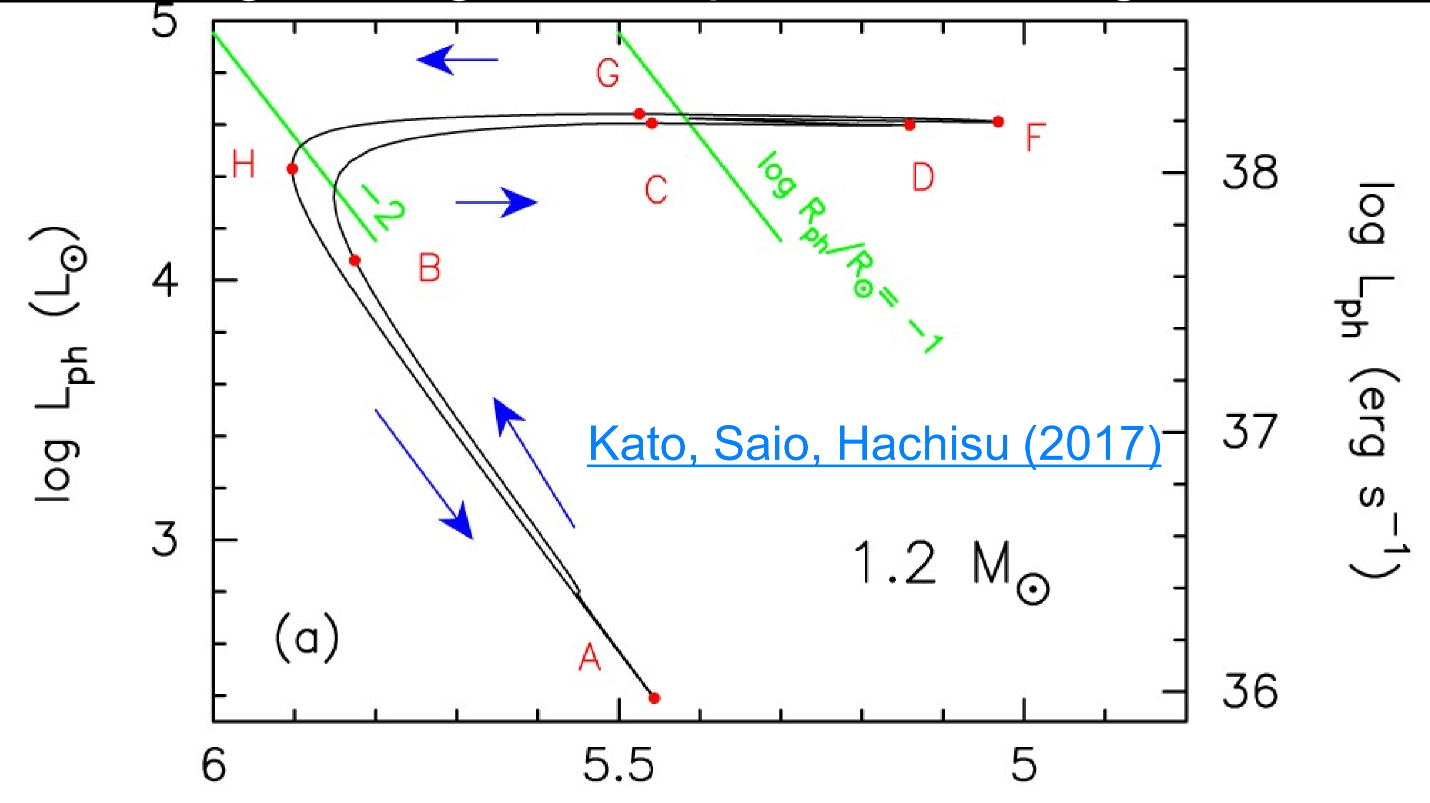


Kato, Saio, Hachisu (2017)

Novae in the HR Diagram (e.g., Hillman et al. 2014; Kato, Saio, Hachisu 2017)

- After $L_{nuc} > L_{Edd}$, $(L_{nuc} – L_{Edd})$ is used for envelope expansion.
  → Photosphere expands rapidly, while $L_{ph} \approx L_{Edd} \approx$ constant.
  → Effective temperature T_{eff} decreases → brightening in the optical wavelength.





Appendix
Supersoft Source (SSS) Phase

- Photosphere Shrink.
  - → Effective temperature increases.
  - → Getting luminous in super soft X-ray.

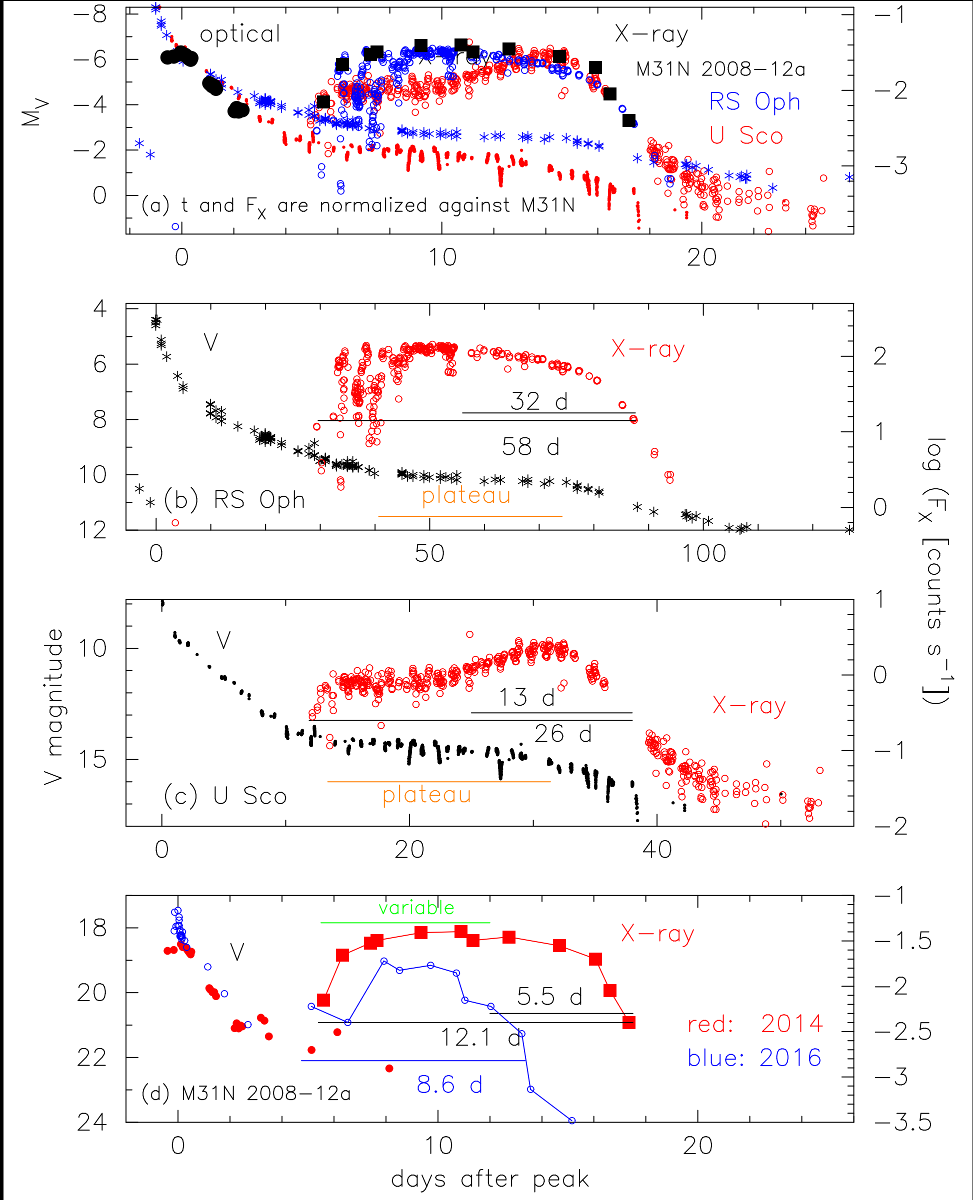


Fig. 1. Comparison of *V* and X-ray light curves among the three recurrent novae M31N 2008-12a, U Sco, and RS Oph. (a) Comparison in normalized timescale against the M31N 2008-12a 2014 outburst. (b) RS Oph. (c) U Sco. (d) M31N 2008-12a in the 2014 (red symbols) and 2016 (blue) outbursts. The horizontal black line segments indicate the duration of the SSS phase, t_{SSS} (long segment) and t^*_{SSS} (short segment). The optical plateau phase is depicted by the horizontal orange line segment in panels (b) and (c). The green horizontal line segment in panel (d) shows the highly variable phase in the 2014 outburst taken from Henze et al. (2015, 2018). The blue horizontal line segment in panel (d) corresponds to t_{SSS} in the 2016 outburst. See text for details. (Color online)

Importance of Initial Brightening Phase in Novae

- Envelope has not expanded so much.
  → The system maybe has not “polluted” by the nova ejecta.
  → Possible key to research on the progenitor accretion stage.
- Real-time observation of launching envelope (ejecta).
- Recently, γ-rays are also observed in initial phases.

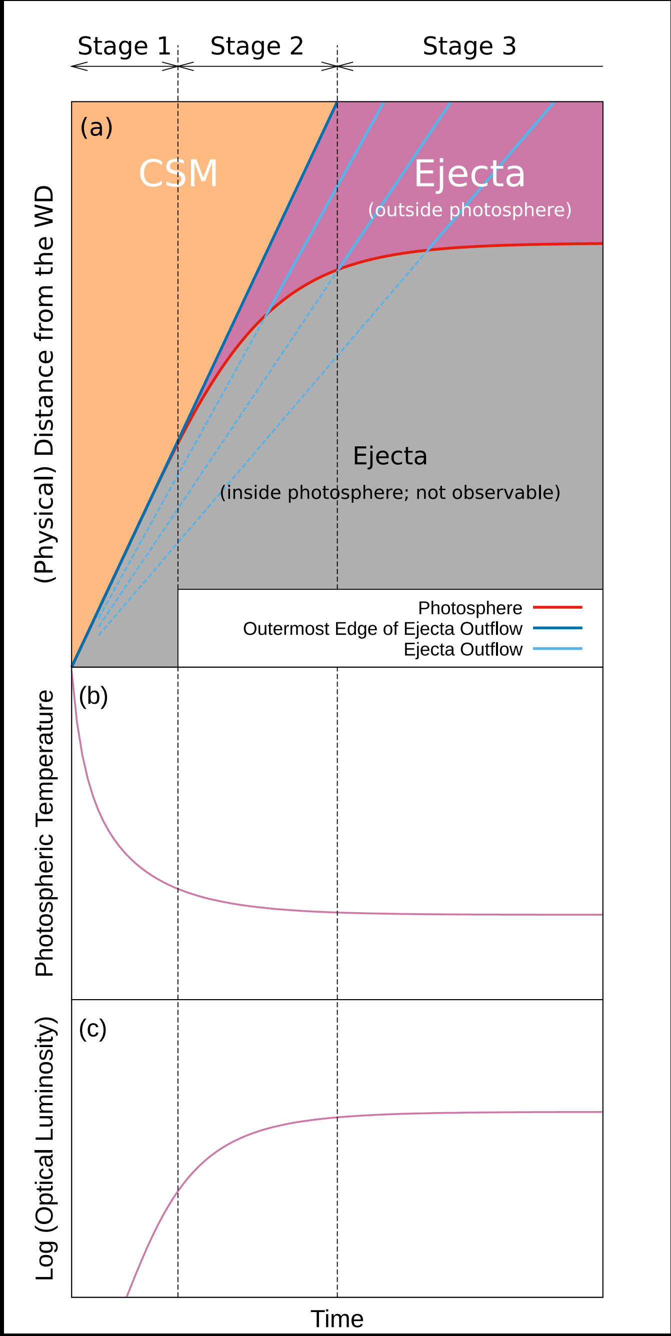
Difficulties in Studying Initial Phases.

- Observations are difficult.
  - Needs prompt discovery and follow-ups.
- “Steady state” approximation is invalid.
  - “Steady state” approximation (e.g., Kato & Hachisu 1994) succeeded in modelling the late phase of novae.

- “Envelope expansion leads brightening” is correct in theory.
  (Observational evidence is few)
- “How envelope expands” is unclear even in theory.

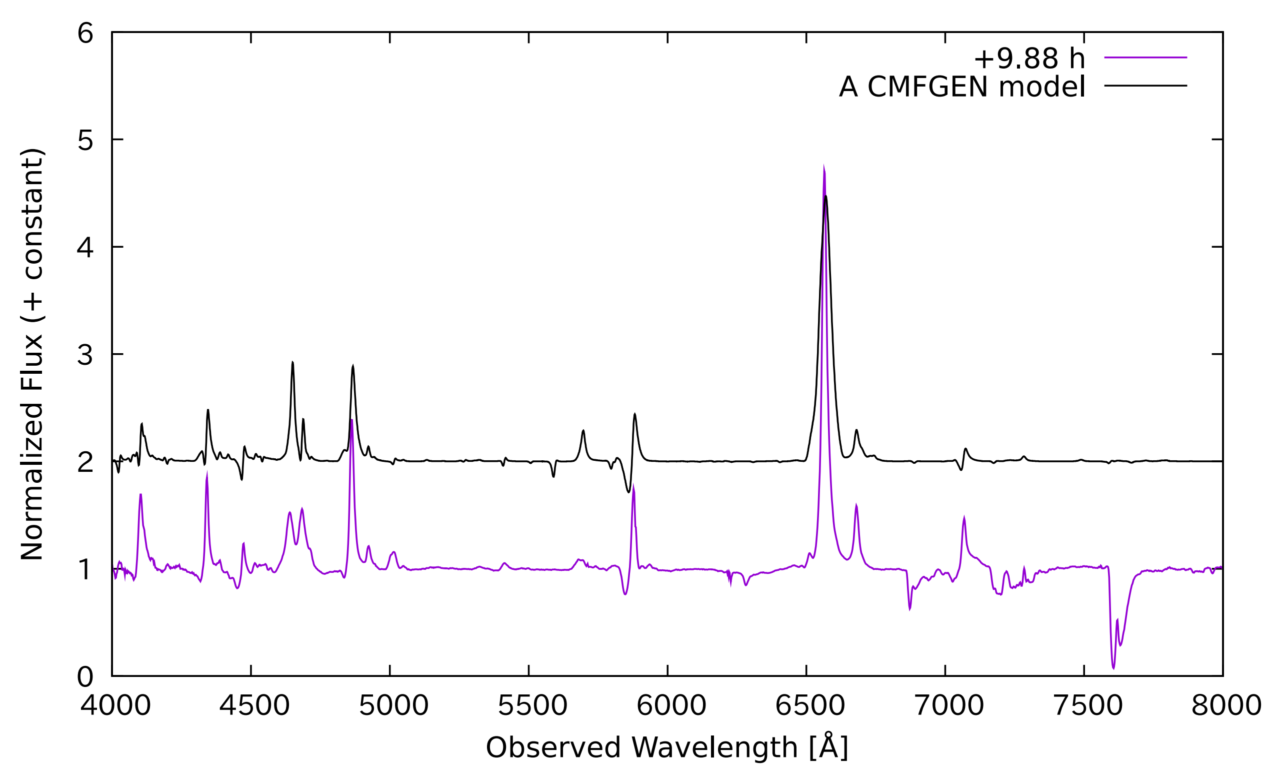
Our Simple Picture

- Stage 1
  - No absorption lines of ejecta are observed.
  - The temperature is highest.
  - Consistent to the T Pyx's spectrum (Arai et al. 2015)
- Stage 2
  - Absorption lines starts to appear.
    - Whose absorption velocities are decreasing.
  - Temperature is still high → high ionized lines are expected.
- Stage 3
  - Around maximum light
  - P Cygni absorption lines.



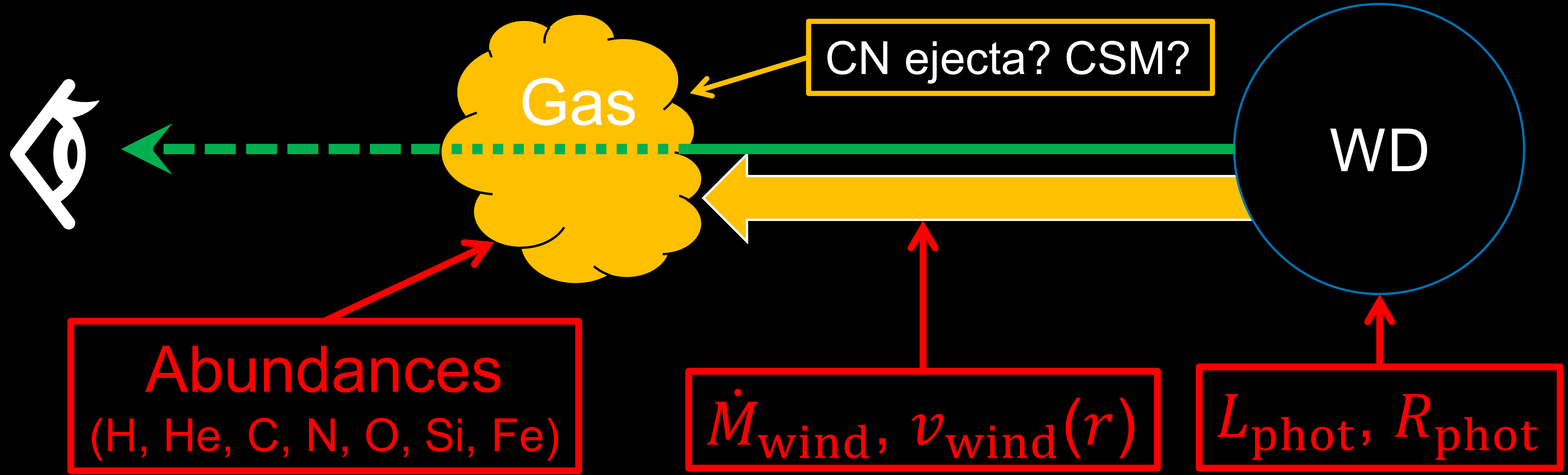
Spectral Modelling

- The key to understanding nova spectra, novae is spectroscopic analysis.
- To compare model and observed spectra is to deduce physical parameters
  - Abundances, density, temperature, ...



About CMFGEN

- We use the radiative transfer code CMFGEN (Hillier and Miller 1998) to calculate the expected spectra of novae of model systems.
  - This code solves non-LTE rate equation, radiative transfer equation, and electron temperature self-consistently in spherical geometry.
  - We regard the structure of nova system (White Dwarf + maybe ejecta) as the same of that of wind-blowing stars, which this code prefers.
  - We approximate nova system steady (like H II regions).



Basic Equations for Spectrum Modelling

- Radiative transfer equation (including scattering in j_ν and α_ν):
  - $\frac{\mathrm{d}}{\mathrm{d}s} I_\nu = j_\nu - \alpha_\nu I_\nu$

  $\rightarrow \left[\mu \frac{\partial}{\partial r} + \frac{1-\mu^2}{r}\frac{\partial}{\partial \mu} - \frac{\nu \mathrm{v}(r)}{rc}\left\{(1-\mu^2) + \frac{\mathrm{d}\ln \mathrm{v}}{\mathrm{d}\ln r}\mu^2\right\}\frac{\partial}{\partial \nu}\right] I_\nu(r,\mu) = j_\nu(r) - \alpha_\nu(r) I_\nu(r,\mu)$

  (for co-moving frame observer with the nova wind in the spherical geometry, non-relativistic)
    - $\mu = \cos\theta$
    - $j_\nu = j_\nu^{\mathrm{continuum}} + \sum_{\mathrm{lines}} j_\nu^{\mathrm{line}} + n_\mathrm{e}\sigma_\mathrm{e} J_\nu$
      - $J_\nu = \frac{1}{4\pi}\int I_\nu \,\mathrm{d}\Omega$
    - $\alpha_\nu = \alpha_\nu^{\mathrm{continuum}} + \sum_{\mathrm{lines}} \alpha_\nu^{\mathrm{line}} + n_\mathrm{e}\sigma_\mathrm{e}$
- Detailed balance between two levels (for non-LTE):
  - $n_l(B_{lu} J_{ul} + C_{lu}) = n_u(A_{ul} + B_{ul} J_{ul} + C_{ul}))$
- Others (Radiative Equilibrium for T_e distribution, radiative force for v(r), ...)

Spectral Modelling

- The key to understanding nova spectra, novae is spectroscopic analysis.
- To compare model and observed spectra is to deduce physical parameters
  - Abundances, density, temperature, ...

- The code doesn't work for last 1 yr.
  - If you've used it, please educate me.