THE RADIAL VELOCITY SEARCH FOR CIRCUMBINARY PLANETS: PLANET DETENCTION LIMITS FOR A SAMPLE OF DOUBLE-LINED BINARY STARS – INITIAL RESULTS FROM KECK 1/HIRES, SHANE /HAMSPEC , AND TNG/SARG OBSERVATION

Konacki et al. 2009

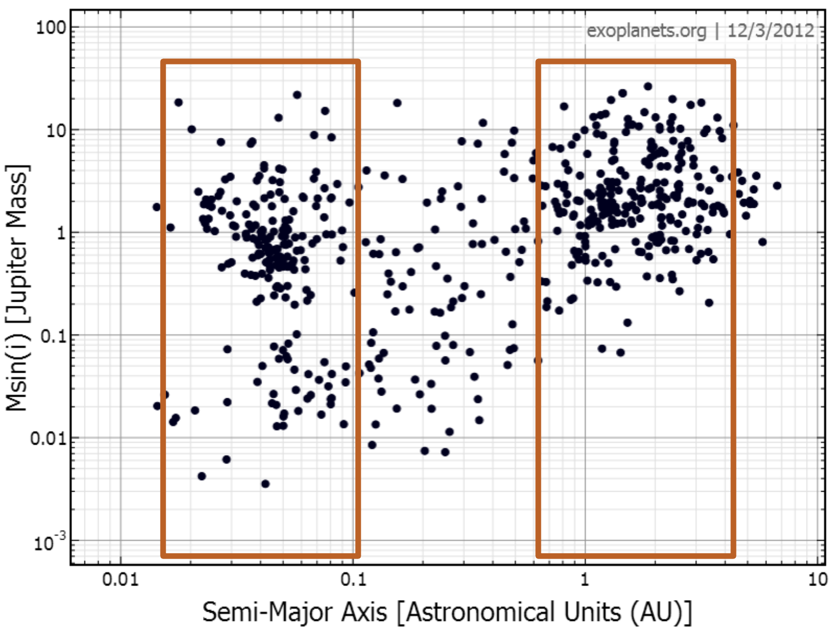
ABSTRACT

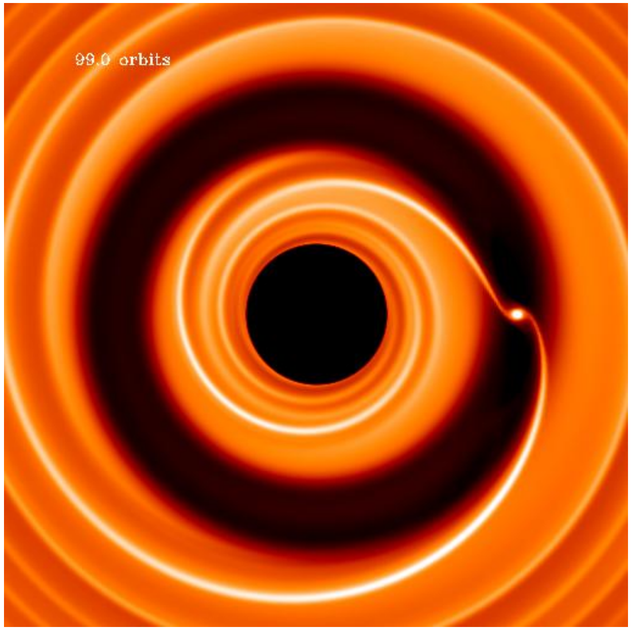
- 現在進行中の連星の惑星サーベイの2003～2008年の結果を紹介します。ヨウ素セルを用いた視線速度法、Keck 1/Hires,TNG/Sarg,Shane/CAT/Hamspec精度2[m/s]用い10個のdouble-lined binaryの探査結果、制限（0.3~3MJup,~up to 5.. years）をこの論文では報告しています。現在の10個のサンプル数で連星系に制限をつけるのはとても難しく、しかし連星に付随する惑星の研究は先進的でありこれからの惑星形成理論に新しい制限をつけるものであります。

INTRODUCTION

~SUBSTANTIALLY DIFFERENT THEN AROUND SINGLE STAR~

- The binarity of the central body creates an environment in which the evolution of a protoplanetery disk is substantially different than around single stars(Artymowicz & Lubow 1994).





- >parking mechanism?

INTRODUCTION ~THEORISTS~

- Dvorack (1984) : framework of the elliptic restricted three-body problem.

1. P-type(planet-type; circumbinary orbits)
2. S-type(satellite-type; circumprimary or circumsecondary orbits)
3. L-type(Librator-type; orbits around Lagrangian points)

- Artymowicz & Lubow (1994)
- Binaryのsemimajor axisの1.8-2.6 times のギャップをあける by tidal torque
- Moriwaki & Nakagawa (2004) and Scholl et al. 2007
- ...shows planetesimal accretion should be possible in circumbinary disks.
- Quintana & Lissauer (2006)
- ...provide numerical proofs that planetary system similar to those around single stars may be formed around binary stars

INTRODUCTION ~OBSERVER~

- There are a few known cases of young spectroscopic binaries with circumbinary disks.
- AK Sco (Andersen et al. 1989)
- GW Ori (Mathieu et al. 1991)
- DQ Tau (Mathieu et al. 1997)
- GG Tau (Dutrey et al. 1994).

- Around a ~12 Myr old close binary V4046 Sgr demonstrating that it is surrounded by a rich molecular disk and showing a great similarity to the~8Myr old star TWHya; a star/disk system regarded a representative ofthe early solar nebula.

INTRODUCTION
~IMPORTANCE OF CIRCUMBINARYS OBSERVATION~

- From theory

>There is enough evidence that circumbinary planets should form

- From observation

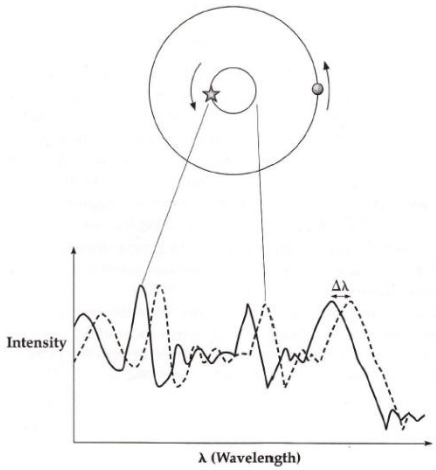
>No RV survey has been carried out.

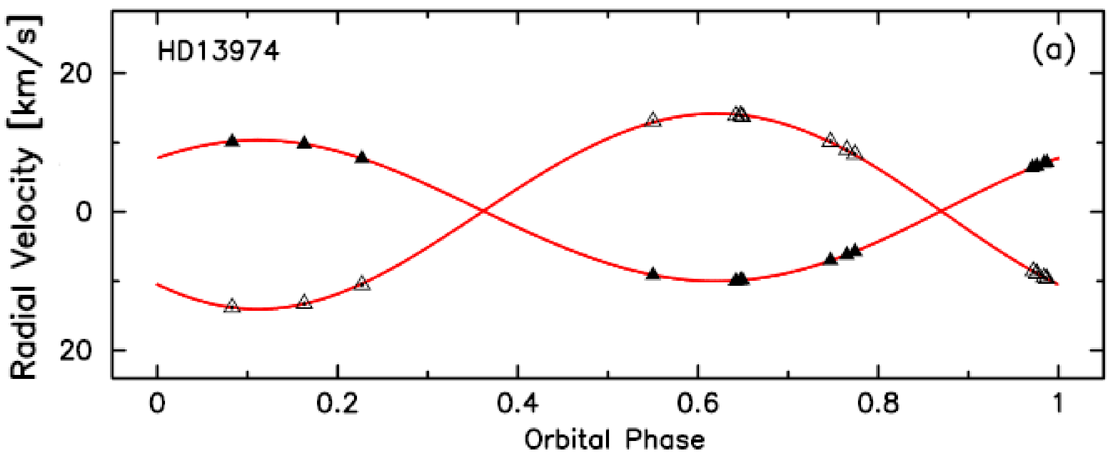
Yet no radial velocity survey has been carried out to detect such planets despite the fact that the RV technique for ingle stars has allowed for a thriving scientific endeavor over the last 15 years

- In this paper, we present the preliminary results of the **first RV survey** for circumbinary planets.

INTRODUCTION ~RADIAL VELICITY PRECISIONS~

- <u>Fundamental problem</u>
- Binary stars spectra is highly variable due to the orbital motion of their components; typically ~ 100[km/s]
- Konacki et al. 2005a,2009 demonstrates a method for obtaing RV precisions of up to 5[m/s] for double-lined spectroscopic binaries.





- Single star spectroscopic (Dumusque et al. 2012)
- Around **Alpha Centauri B: 80[cm/s]**
- By HARPS 3.6[m], R=110,000@La Silla Observatory
- Distance ~ **1.3[pc]** From our system

Precision RVs of double-lined spectroscopic binaries ~Iodine techniques~

- Iodine technique

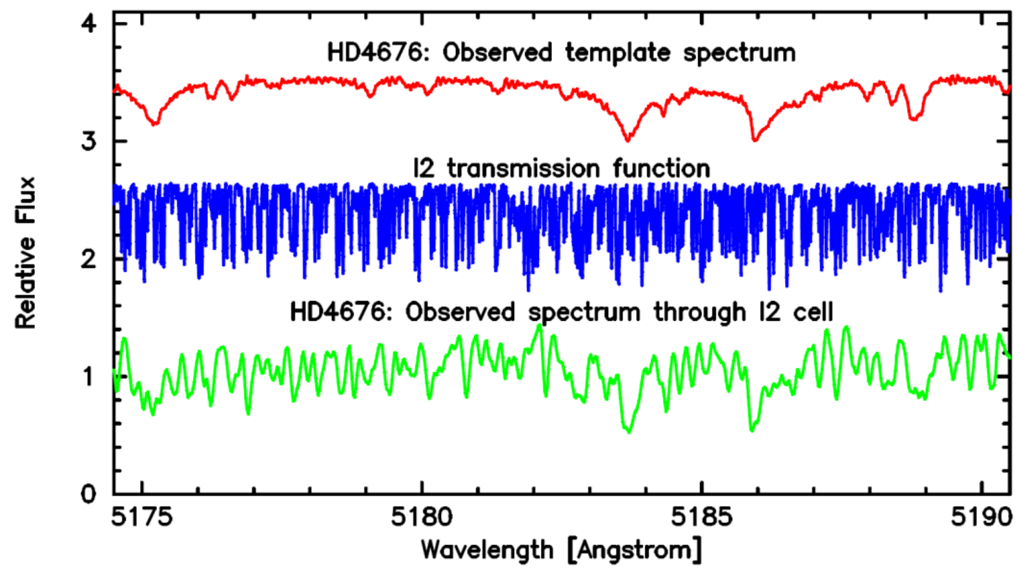
$$I_{\mathrm{obs}}(\lambda) = [I_s(\lambda + \Delta\lambda_s)\, T_{I_2}(\lambda + \Delta\lambda_{I_2})] \otimes \mathrm{PSF}$$

観測値 星 ヨウ素による吸収

- High SNR star spectrum taken w/o the cell **as a template for all spectra** with cell
- I_2 transmission function

$$\Delta\lambda = \Delta\lambda_s - \Delta\lambda_{I_2}$$

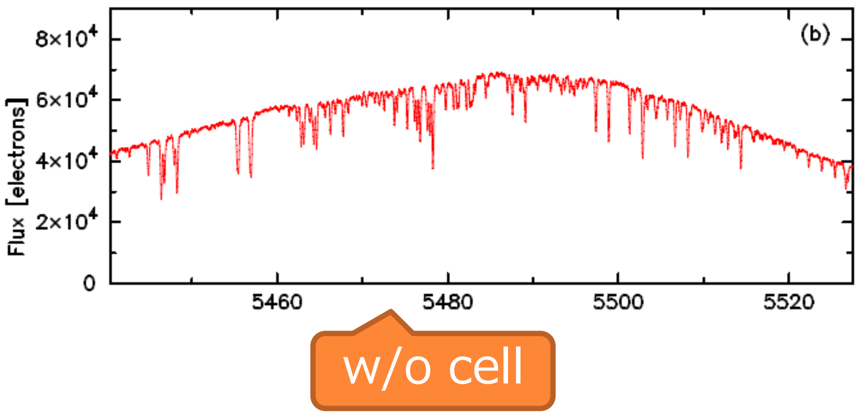
- ...such an iodine technique can only applied be to single stars.
- >

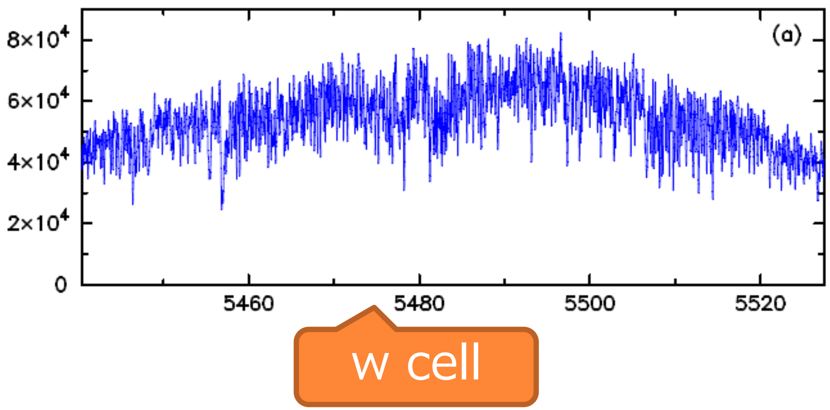


Konacki et al. 2010

Precision RVs of double-lined spectroscopic binaries ~iodine techniques for double lined binary~

- >Double-lined binary spectra is always composite and time variable
- ①take two subsequent exposures of a binary target; w and w/o iodine cell



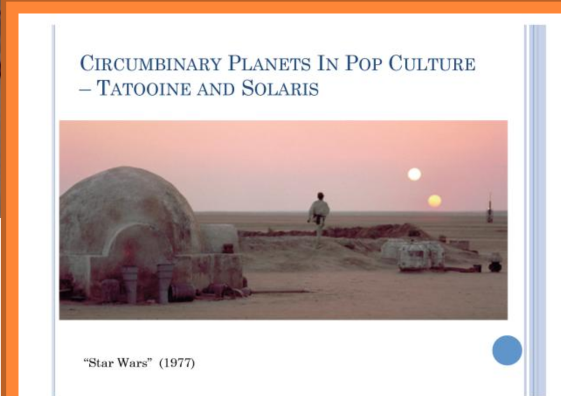


- ②perform usual least-squares fit and obtain parameters described in

$$I_{\rm obs}(\lambda) = [I_s(\lambda + \Delta\lambda_s)\, T_{I_2}(\lambda + \Delta\lambda_{I_2})] \otimes \mathrm{PSF}$$

The tatooine survey ~What is "TATOOINE"?~

- To Attempt To Observe Outer-planets In Non-single-stellar Environments
- Initiated in mid 2003



Kocackiが作ったスライド

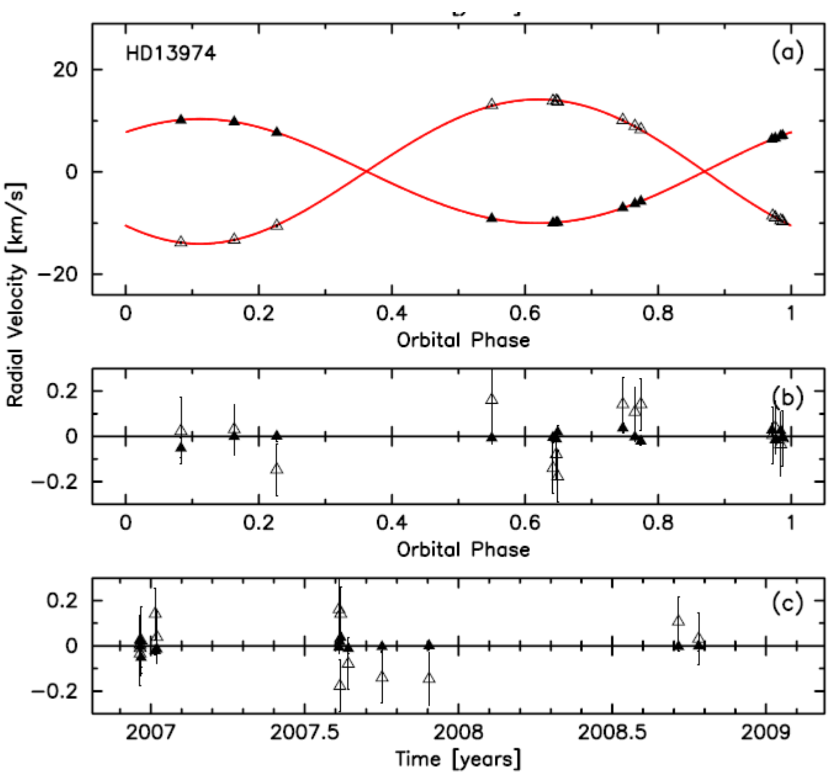
THE TATOOINE SURVEY~OBSERVATION~

- Exposure w iodine cell
- Exposure w/o iodine cell
- Balance the resulting S/N (depending on the telescope)

instrument	epoch	resolution @400-(500-600)-900	S/N	Diameter [m]
Keck 1/HIRES	until mid 2007	67000	250	10
TNG/Sarg	from mid 2006 until mid 2007	86000	75-150	3.6
Shane/CATs/ HamSpec	since fall 2006	60000	50-150	3, 0.6

- Different precision raiging ~2 to 20 [m/s].
- Enough precision to detect as small as $0.3M_{Jup}(=100M_{earth})$

THE TATOOINE SURVEY~ANALYSIS~



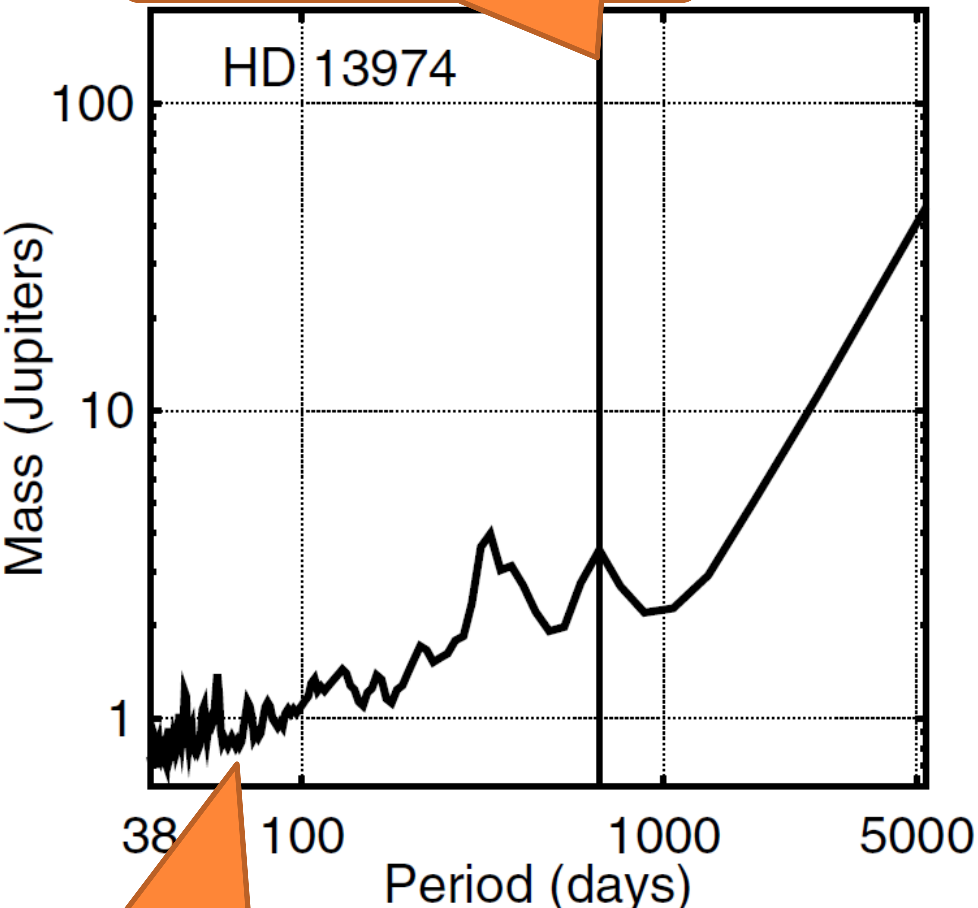
- **Error**
- The internal RV errors

  >expected to underestimate the real RV scatter
- Stellar jitter

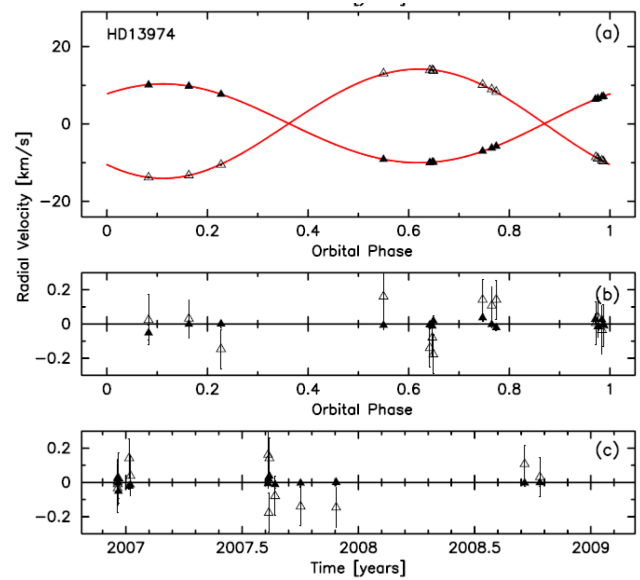
  > these imperfection are impossible to see with "naked eye"
- We add an additional error in quadrature to obtain a reduced **χ^2=1 for a single Keplerian model**.

Planet detection (limits) for del Tri(HD13974)

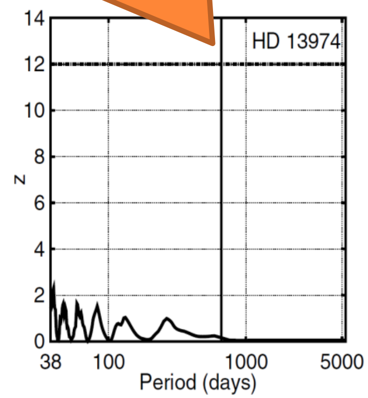
Time span of data set



99% confidence



1% False Alarm Probability



$$z = Q\frac{\chi_{\circ}^{2} - \chi^{2}}{\chi^{2}_{\mathrm{min,circ}}},$$

$$Q_{\mathrm{circ}} = \frac{N_D - (2 + N_{v_{\circ,i}})}{2}$$

TARGETS DATA AND THEIR RV DATA SETS

Table 1
Targets and Their Radial Velocity Data Sets

Parameter	HD 9939	HD 13974	HD 47415	HD 78418	HD 86146	HD 195987	HD 210027	HD 214686	HD 221950	HD 282975
V (mag)	6.99	4.9	6.38	5.98	5.12	7.09	3.76	6.89	5.70	10.0
Sp	K0IV	G0V	F5V/F5V	G5IV-V	F5V/G0V	G3V/K2V	F5V/G8V	F7V/F7V	F6V	G6V
r	6.3	6.2	1.7	2.3	2.5	6.7	12	1	1.25	1.1
M_1 ($M_\odot$)	1.072[a]	0.6[b]	1.4[c]	1.15[c]	1.35[d]	0.844[e]	1.326[f]	1.25[g]	1.31[g]	1.0[h]
M_2 ($M_\odot$)	0.8383[a]	0.5[b]	1.2[c]	1.0[c]	1.08[d]	0.665[e]	0.819[f]	1.25[g]	1.24[g]	0.9[h]
$P_{\rm orbital}$ (days)	25.2	10.0	5.7	19.4	9.3	57	10.2	21.7	45.5	26
$a_{\rm stable}$ (AU)	0.61	0.23	0.21	0.61	0.28	1.25	0.29	0.85	1.37	0.97
$P_{\rm stable}$ (days)	126	38	22	117	35	416	38	179	365	251
All RVs										
$N_1 + N_2$	34	28	44	50	62	50	146	22	22	32
$T_{\rm span}$ (days)	1513	663	1695	1695	701	1474	1925	646	681	1238
rms$_1$ (m s^{-1})	19.5	22.5	12.8	11.5	15.2	11.0	17.2	14.6	48.4	21.9
rms$_2$ (m s^{-1})	36.0	111.1	25.6	25.0	67.6	48.0	85.2	14.7	29.8	12.5
Keck I/Hires										
$N_1 + N_2$	20	...	30	26	...	22	104	...	...	32
rms$_1$ (m s^{-1})	6.8	...	12.8	9.9	...	2.3	16.5	...	...	21.9
rms$_2$ (m s^{-1})	21.4	...	10.6	14.7	...	24.8	89.0	...	...	12.5
σ_1 (m s^{-1})	1–4	...	4–11	2–6	...	3–6	5–32	...	...	4–17
σ_2 (m s^{-1})	4–10	...	5–11	4–10	...	7–18	12–65	...	...	7–15
ϵ_1 (m s^{-1})	6	...	11	5.5	...	0	12	...	...	20
ϵ_2 (m s^{-1})	21	...	8	4	...	20	85	...	...	11
Shane/CAT/Hamspec										
$N_1 + N_2$	14	28	14	24	62	18	30	22	22	...
rms$_1$ (m s^{-1})	14.0	22.5	12.3	12.0	15.2	14.2	20.4	14.6	48.4	...
rms$_2$ (m s^{-1})	57.3	111.1	37.3	31.0	67.6	72.2	85.5	14.7	29.8	...
σ_1 (m s^{-1})	4–14	7–38	5–21	4–27	6–34	7–17	7–26	11–26	7–56	...
σ_2 (m s^{-1})	9–73	13–91	8–39	6–35	13–63	20–53	16–100	9–27	8–55	...
ϵ_1 (m s^{-1})	20	19	8	11	7	13	18.5	0	48	...
ϵ_2 (m s^{-1})	30	110	30	37	58	50	68.0	8	32	...
TNG/Sarg										
$N_1 + N_2$	...	...	...	...	...	10	12	...	...	...
rms$_1$ (m s^{-1})	...	...	...	...	...	5.1	19.4	...	...	...
rms$_2$ (m s^{-1})	...	...	...	...	...	15.8	89.9	...	...	...
σ_1 (m s^{-1})	...	...	...	...	...	6–12	10–20	...	...	...
σ_2 (m s^{-1})	...	...	...	...	...	11–17	45–72	...	...	...
ϵ_1 (m s^{-1})	...	...	...	...	...	0	12	...	...	...
ϵ_2 (m s^{-1})	...	...	...	...	...	36	38	...	...	...

COCLUSION

- The search for Circumbinary planets will constraints for the planet formation theories.

  >very important!

- TATOOINE, radial velocity search for circumbinary planets around a sample of ~50 SB2s.

  >from 2003

- A non-detenction of exoplanets in the 0.3-3 M_{jup} regime with the period of up to 5.3 years around 10 SB2s.