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Properties of Hypothetical Planetary Systems around the Brown Dwarf Gliese 229B

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ABSTRACT. Up to now, the occurrence of planetary systems around brown dwarfs has not been studied in detail. However, there is no reason to exclude the occurrence of planets around brown dwarfs. Moreover, their smaller mass with respect to normal stars makes more prominent the effects due to the presence of planets, allowing in principle the identification of planets with smaller masses (i.e., Earth-like planets). In this paper we present a feasibility study of the detection of planetary companions around the brown dwarf Gliese 229B ($M = 0.025$–$0.055\ M_{\odot}$) using near-infrared high-resolution spectroscopy to measure radial velocity variations. Issues concerning the intrinsic stability of brown dwarfs as well as instrument requirements are considered.

1. INTRODUCTION

Brown dwarfs (BDs) have been recently identified as isolated field objects, in binary systems, open clusters, and star formation regions (see Rebolo et al. 1998a; Oppenheimer et al. 1998b; Tinney 1999 for updated reviews). Up to now, the occurrence of planetary systems around BDs has not been extensively considered. However, the indications for the presence of active accretion disks around some BD candidates in star-forming regions (Hillenbrand et al. 1998; Wilking et al. 1999),[1] the occurrence of planetary systems around stars with different masses,[2] as well as the satellite system around a giant planet such as Jupiter suggest that there is no reason to exclude planets around BDs. Moreover, the smaller mass of BDs with respect to normal stars makes more prominent the effects due to the presence of planets, allowing in principle the identification of planets with smaller masses, down to Earth-like planets. In this paper, we present a feasibility study of the detection of planetary companions around the BD Gliese 229B, as a prototype of an old low-mass BD (Nakajima et al. 1995), using high-precision spectroscopy to measure radial velocity (RV) variations. Its quite old age is expected to lead to a better RV stability. Alternative methods for identification of planets such as astrometry and transit monitoring are not discussed here.

The paper is organized as follows: § 2 describes the expected RV variations from planets with different masses and orbital radii around Gl 229B; § 3 reports an estimate of the temperature of these hypothetical planets to check the possibility of identifying true Earth analogs; § 4 considers the physical phenomena that could hide the occurrence of planets around BDs; in § 5 the technical feasibility of this project and instrument requirements are considered. Finally, § 6 reports a summary of the identified BDs and a preliminary estimate of the number of possible targets, apart from Gl 229B.

2. RADIAL VELOCITY VARIATIONS

In this section we compute the RV variations for a series of hypothetical planetary companions around the brown dwarf Gl 229B. Mass estimates for Gl 229B cover the range 0.02–0.055 $M_{\odot}$ ($\sim$20–55 M_J).[3] In the following we discuss two cases: $M = 0.05$ and 0.025 $M_{\odot}$ (about 50 and 25 M_J, respectively). Considering only circular orbits, the RV semi-amplitude K is given by

$$\frac{K}{\sin i} = 0.42 \frac{M_p}{\sqrt{a}} \text{ m s}^{-1} , \quad (1)$$

$$\frac{K}{\sin i} = 0.59 \frac{M_p}{\sqrt{a}} \text{ m s}^{-1} , \quad (2)$$

[1] Actually, Hillenbrand et al. (1998) find a lower disk frequency for the lowest mass ($M < 0.2\ M_{\odot}$) members of the Orion Nebula cluster (20%–50% vs. 50%–90% for the cluster as a whole). This can be due to the high star density of this cluster that favors stripping of the disk around smaller objects or to some other intrinsic reason due to smaller mass.

[2] Most of the extrasolar planets identified so far are around solar-type star. This is due mainly to bias on sample selection. Recently, Delfosse et al. (1998) and Marcy et al. (1998) identified a giant planet around the 0.3 $M_{\odot}$ star Gl 876.

[3] The recent photometry of Gl 229 by Leggett et al. (1999) suggests a lower mass (0.025 $M_{\odot}$) and a lower age (0.5 Gyr) with respect to previous estimates ($M = 0.04$–$0.05\ M_{\odot}$, age older than 1 Gyr).

for $M = 0.050\ M_\odot$ and $M = 0.025\ M_\odot$, respectively, where i is the inclination of the orbital plane, M_p the mass of the planet in $M_\oplus$, and a the orbital semimajor axis in AU. Periods are calculated by scaling the Kepler's third law to the mass of Gl 229B. This becomes

$$P(\mathrm{yr}) = 4.47a^{3/2}(\mathrm{AU})\ \mathrm{yr} = 1632.7a^{3/2}(\mathrm{AU})\ \mathrm{days}\ , \quad (3)$$

$$P(\mathrm{yr}) = 6.32a^{3/2}(\mathrm{AU})\ \mathrm{yr} = 2308.4a^{3/2}(\mathrm{AU})\ \mathrm{days}\ , \quad (4)$$

for $M = 0.050\ M_\odot$ and $M = 0.025\ M_\odot$, respectively.

We have checked the RV variations applying equations (1)–(4) to five possible planetary systems around Gl 229B: (*a*) a solar system analog (Jupiter, Earth, Venus); (*b*) a "scaled" solar system calculated simply by scaling down the mass of the planets proportionally to the mass of Gl 229B (i.e., Gl 229B has a mass 20 times [if $M_{\mathrm{Gl\,229B}} = 0.050\ M_\odot$] or 40 times [if $M_{\mathrm{Gl\,229B}} = 0.025\ M_\odot$] smaller than the Sun, so we consider its "Jupiter" as a planet 20 [40] times less massive than Jupiter and so on) while the orbital radius is scaled using the same dependence of the limit of tidal destruction (Roche radius) on mass ($R_{\mathrm{TD}} \sim M^{1/3}$, thus for Gl 229B planets a is $20^{1/3} = 2.7$ or $40^{1/3} = 3.4$ times smaller than corresponding solar system planets); (*c*) a "scaled" version of the Jupiter satellite system, calculated as above (i.e., increasing the mass of the satellites by 50 or 25 times and the orbital radius by $50^{1/3} = 3.6$ or $25^{1/3} = 2.9$ times); (*d*) planets near the limit of tidal destruction; (*e*) the 51 Peg system and its "scaled" version.

Tables 1 and 2 report a few examples of the application of equations (1)–(4), while Figure 1 shows the expected RV semiamplitude for planets of 1, 5, and 10 $M_\oplus$ around Gl 229B as a function of orbital semimajor axis.

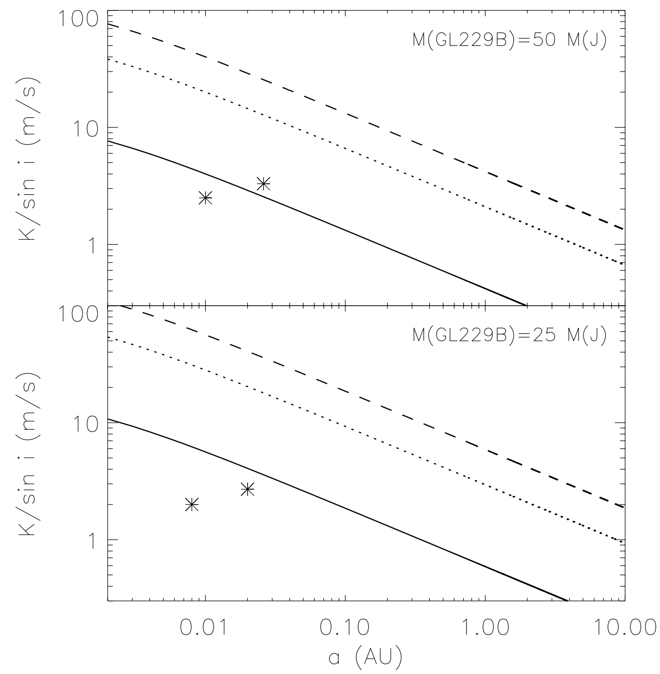

FIG. 1.—Radial velocity semiamplitude from eq. (1) ($M_{\mathrm{Gl\,229B}} = 0.050\ M_\odot$, *top panel*) and eq. (2) ($M_{\mathrm{Gl\,229B}} = 0.025\ M_\odot$, *bottom panel*) for planets of 1 (*solid line*), 5 (*dotted line*), and 10 (*dashed line*) $M_\oplus$ around the brown dwarf Gl 229B. Asterisks represent the "scaled" Io and Ganymede described in the text.

2.1. Solar System Analog

A Jupiter-mass planet at 5.2 AU would induce an RV semiamplitude of 59 m s^{-1} with a period of 53 yr or 82 m s^{-1} with a period of 75 yr for $M = 0.050\ M_\odot$ and

TABLE 1

RADIAL VELOCITY SEMIAMPLITUDE AND PERIOD FOR PLANETS AROUND Gl 229B ($M = 0.050\ M_\odot$)

M ($M_\oplus$)	a (AU)	P	$K/\sin i$ (m s^{-1})	Remarks
1	1	4.47 yr	0.4	Earth-like
0.8	0.72	2.73 yr	0.4	Venus-like
318	5.2	53.0 yr	59	Jupiter-like
15.8......	1.9	11.7 yr	4.8	"Scaled" Jupiter
0.6	0.01	1.63 days	2.5	"Scaled" Io
1.28......	0.026	6.8 days	3.3	"Scaled" Ganymede
1	0.01	1.63 days	4.2	Earth mass at scaled Io position
159	0.05	18.2 days	300	51 Peg B–like
8	0.02	4.1 days	24	"Scaled" 51 Peg B
1	0.2	146 days	0.9	Earth mass at tidal locking limit
1	0.0027	0.23 days	8.1	Earth mass at R_{TD}
1	0.0054	0.65 days	5.7	Earth mass at $2R_{\mathrm{TD}}$

TABLE 2

Radial Velocity Semiamplitude and Period for Planets around Gl 229B ($M = 0.025\ M_\odot$)

M ($M_\oplus$)	a (AU)	P	$K/\sin i$ (m s^{-1})	Remarks
1.0	1.0	6.3 yr	0.6	Earth-like
0.8	0.7	3.9 yr	0.6	Venus-like
318	5.2	74.9 yr	82.3	Jupiter-like
8	1.5	11.6 yr	3.8	"Scaled" Jupiter
0.3	0.008	1.6 days	2.0	"Scaled" Io
0.64......	0.020	6.8 days	2.7	"Scaled" Ganymede
1.0	0.008	1.6 days	6.6	Earth-like at scaled Io position
159	0.05	25.8 days	420.0	51 Peg B–like
4	0.015	4.2 days	19.2	"Scaled" 51 Peg B
1.0	0.2	206 days	1.3	Earth-like at tidal locking limit
1.0	0.002	0.21 days	13.1	Earth mass at R_{TD}
1.0	0.004	0.58 days	9.3	Earth mass at $2R_{TD}$

$M = 0.025\ M_\odot$, respectively. Such a planet is likely not allowed to exist in stable orbit, because of the effects of Gl 229A (see below).

An Earth-mass planet at 1 AU leads to an RV semiamplitude of 0.4 and 0.6 m s^{-1} for the two Gl 229B mass assumptions. These variations are clearly very small, although significantly larger than the case of the Sun (0.09 m s^{-1}).

2.2. "Scaled" Version of Solar System around Gl 229B

The "scaled" Jupiter would have a mass of $M = 15.9\ M_\oplus$ (i.e., Uranus size) and $M = 8.0\ M_\oplus$ and an orbital radius $a = 1.9$ and 1.5 AU for $M = 0.050\ M_\odot$ and $M = 0.025\ M_\odot$, respectively. The corresponding RV semiamplitudes are $K/\sin i = 4.8$ and 3.8 m s^{-1} with a period of 11.7 yr (the same as true Jupiter). This long period would make difficult the identification of such small variations. Inner Earth and Venus "scaled" planets would have a very small mass (about 0.05 $M_\oplus$), and the corresponding RV variations would amount to 0.01 m s^{-1}.

2.3. Jupiter-like Satellite System around Gl 229B

An interesting comparison can be performed by scaling up the Jupiter satellite system to the mass of Gl 229B (nearly 50 and 25 M_J). Io is 0.0028 AU from Jupiter, with a mass of 0.012 $M_\oplus$. If the "Io satellite" of Gl 229B has a mass 50 (25) times higher and an orbital radius $50^{1/3} = 3.6$ ($25^{1/3} = 2.9$) times larger, we obtain a mass of 0.6 (0.3) $M_\oplus$ and an orbital radius of 0.010 (0.008) AU. This distance is about 3.5 times the limit of tidal destruction.

This implies an RV semiamplitude of 2.5 (2.0) m s^{-1} with a period of 1.6 days. An Earth-mass planet at the same distance has $K/\sin i = 4.2$ m s^{-1} for $M = 0.050\ M_\odot$ and 6.6 m s^{-1} for $M = 0.025\ M_\odot$.

A Ganymede-like satellite has a mass of 1.28 or 0.64 $M_\oplus$ (50 or 25 times the real Ganymede) and an orbital radius of 0.026 or 0.020 AU. The corresponding RV semiamplitudes are 3.3 and 2.7 m s^{-1} with a period of 6.8 days.

We conclude that a "scaled" Jupiter-like satellite system around Gl 229B corresponds to Earth-size planets producing RV semiamplitudes of a few m s^{-1} (if $i \sim 90°$), with periods of a few days. A multibody system should produce multiperiodic RV variations, making more challenging the interpretation of the data.

2.4. Limit of Tidal Destruction for Planets around Gl 229B

The limit of tidal destruction of a planet around a primary body is given by

$$R_{TD} = 2.46\left(\frac{\rho_*}{\rho_p}\right)^{1/3} R_* \,, \tag{5}$$

where ρ_* and ρ_p are mean density of the central body and the planet, respectively, and R_* is the radius of the central body.

Assuming for Gl 229B $R_* = 0.1\ R_\odot$, independent of mass (a good approximation for old low-mass BDs; see Burrows & Liebert 1993), we obtain $\rho_* = 66$ and 33 g cm^{-3} for $M = 0.050$ and 0.025 $M_\odot$, respectively. Thus the limit of tidal destruction of an Earth-like planet ($\rho_p = 5.5$ g cm^{-3}) is $R_{TD} = 0.0027$ and 0.0020 AU for $M = 0.050$ and 0.025, respectively.

Formally a 1 $M_\oplus$ planet at these orbital radii should cause an RV semiamplitude $K/\sin i = 8.1$ and 13.1 m s^{-1} for $M = 0.050$ and 0.025, respectively. These are the upper limits of RV variations caused by Earth-mass planets.

Clearly the formation of massive planets at such small orbital radii is quite unlikely to occur. However, orbital migration could be at work, as suggested by the existence of 51 Peg–type systems.

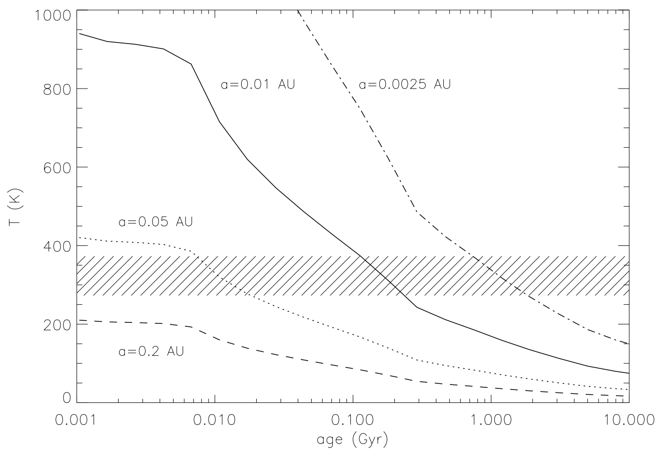

FIG. 2.—Temperature evolution for planets at 0.0025 (*dash-dotted line*), 0.01 (*solid line*), 0.05 (*dotted line*), and 0.2 (*dashed line*) AU around a 0.04 $M_\odot$ brown dwarf from the models of Burrows et al. (1997). Hatched region is the formally habitable zone ($T = 273$–373 K).

2.5. "Scaled" Version of 51 Peg System around Gl 229B

Most of the extrasolar planets identified so far are giant planets at small orbital radii (Marcy & Butler 1998). Thus, we compute the properties of a 51 Peg–like ($M = 0.5\ M_J$, $a = 0.05$ AU; Mayor & Queloz 1995) system around Gl 229B. Scaling down mass and orbital radius as above (assuming a solar mass for 51 Peg) we obtain a mass of 8 (4) $M_\oplus$ and an orbital radius of 0.02 (0.015) AU for our two mass assumptions. The corresponding RV semiamplitudes are 24 and 19 m s^{-1} with a period of 4.1 days.

A planet as massive as 51 Peg B at $a = 0.05$ AU would imply a much higher RV variation (300 and 420 m s^{-1} for $M = 0.050$ and 0.025, respectively).

2.6. Summary of RV Variations

These calculations demonstrate that Earth-mass planets around Gl 229B would induce RV variations of 1 m s^{-1} (assuming favorable orbital inclination) for orbital radii within 0.2 AU, reaching 10 m s^{-1} near the limit of tidal destruction. The analogy with the Jupiter satellite system makes this hypothesis not unrealistic. The RV variation of a 10 $M_\oplus$ planet reaches 10 m s^{-1} at 0.2 AU and 100 m s^{-1} near the limit of tidal destruction.

3. TEMPERATURE

The average effective temperature on the planet's surface can be calculated using the following equation:

$$T \sim T_*\left(\frac{R_*}{2a}\right)^{1/2}(1 - A)^{1/4}\ , \qquad (6)$$

where T is the temperature of the planet, T_* and R_* the temperature and radius of the star, a the orbital radius of the planet, and A its albedo. Including the parameters of Gl 229B ($R \sim 0.1\ R_\odot$, $T_{\rm eff} = 900$ K) and assuming $A = 0.15$ (Earth-like planet under near-infrared stellar irradiation; Kasting et al. 1993), equation (6) becomes

$$T = 13.2\,\frac{1}{\sqrt{a({\rm AU})}}\ {\rm K}\ . \qquad (7)$$

Near the limit of tidal destruction ($a = 0.0025$ AU), the blackbody temperature should be 264 K, formally very near the habitable zone ($T = 273$–373 K). This value is only indicative because atmospheric phenomena such as the greenhouse effect are not taken into account and can lead to very different temperatures.[4] Moreover, at such small orbital radii tidal heating is expected to be significant, at least at earlier phases. Thus the present habitable zone around Gl 229B could be at somewhat larger orbital radii (0.005–0.01 AU). A planet at 0.01 AU (scaled Io) would have a blackbody temperature of about 130 K.

Planets in such inner orbits would rotate synchronously with their orbits. The radius of tidal locking is expected to be at about 0.2 AU for the Gl 229B mass (Kasting et al. 1993). In this case very strong temperature differences are expected between the bright and dark sides of the planet, leading to permanent freezing of volatiles on the dark side.

A final remark is that BDs such as Gl 229B are much hotter during the earlier evolutionary phases. Their temperature changes very sharply during the first Gyr and consequently also the temperature of the planets around them. Figure 2 shows the temperature evolution of planets at 0.0025, 0.01, 0.05, and 0.2 AU around a 0.04 $M_\odot$ BD taking into account the luminosity evolution of the primary (from the models of Burrows et al. 1997, their Table 4). It can be seen that Earth-like planets around young BDs could have liquid water but only for a short period of time (0.1–0.2 Gyr at 0.01 AU, 0.8–2.0 Gyr at 0.0025 AU, still neglecting greenhouse and tidal heating effects). However, the very high temperature at such small distances during the first Myr (≥ 1000 K) should likely lead to water loss via photolysis and hydrogen escape. Planets escaping synchronous rotation ($a > 0.2$ AU) should have a temperature of about 30 K at the present epoch. They are not expected to be within the habitable zone even at their very early stages.

4. SCIENTIFIC CHALLENGES

4.1. Rotation

The rotation period of Gl 229B is unknown. Some BDs and very low mass stars are seen to be rapidly rotating (Tinney & Reid 1998; Martin et al. 1997, 1998), with rota-

[4] Application of eq. (6) to Venus and Earth gives $T = 230$ and 246 K, respectively, very different from the actual values ($T = 730$ and 288 K) in the case of Venus.

tional velocities up to $v \sin i \sim 20$–40 km s^{-1}. All these objects are likely younger than Gl 229B. The rotation velocity of Jupiter is about 12 km s^{-1}.

In the following, two cases for Gl 229B are considered: $v \sin i = 10$ and 20 km s^{-1} (larger rotational velocity probably concerns only younger BDs).

The rotation period resulting from such velocities (6–12 hr, assuming $R = 0.1\ R_\odot$) is faster than the orbital periods for planets at a larger than about 0.004 AU. In principle, this could allow one to disentangle RV variations due to rotation-related causes from those due to other phenomena such as gravitational effects by planetary companions.

At smaller distances, near the tidal limit, rotation periods of BDs and the orbital period of the planet is expected to be similar. This would make more challenging the interpretation of the data.

Another effect of stellar rotation is the broadening of spectral lines, which increases errors on RV determinations. This point is discussed in § 5.

4.2. Radial Velocity Stability of Brown Dwarfs

At present the intrinsic RV stability of BDs is unknown. Rapidly rotating low-mass stars do not have a good RV stability, because of activity-related phenomena such as star spots, nonuniform convection, flares, and so on (Saar et al. 1998). However, in spite of the large rotation velocity, very low mass stars and BDs do not show prominent chromospheric activity. It seems that for these objects rotation and chromospheric activity are no longer correlated, at odds with low-mass stars down to 0.1 $M_\odot$ (Tinney & Reid 1998; Martin et al. 1998; Basri & Marcy 1995). This is an indication of low magnetic activity, and consequently a better RV stability is expected.

Surface inhomogeneities such as stellar spots alter the line profile, leading to spurious RV variations (Saar & Donahue 1997). Their characteristic timescales are the rotation period and the lifetime of these features. Magnetically induced spots should be weak or absent in BDs (Tinney & Trolley 1999), because of the small level of chromospheric activity. However, at the very low temperature of Gl 229B (900 K) formation of clouds is expected (Burrows & Sharp 1999), and these features can worsen the RV stability of BDs. Recently some BDs and very low mass stars were searched for short-period photometric variations due to rotational modulations (Terndrup et al. 1999; Bailer-Jones & Mundt 1999), with negative results except two (likely stellar) objects: CFHT-PL8 and 2M 1145. Tinney & Trolley (1999) have searched for narrowband variability in two BDs. Their preliminary results seem to indicate the presence of variability in one of their targets (LP 944-20). Photometric variability should imply a quite large area coverage of clouds; in this case the RV variations are expected to be significant.

We conclude that at present it is not clear if the RV stability of old BDs permits detection of the RV perturbations due to an Earth-mass planet. If this is not the case, high-precision RV determinations would instead shed light on BDs' meteorology, a very interesting topic thanks to the similarity of old low-mass BDs such as Gl 229B and giant planets.

4.3. The Presence of Gl 229A

Gl 229 is a binary system, consisting of an M1 V primary (Gl 229A) and the BD Gl 229B, at a projected distance of 44 AU (8″ on the sky). The presence of the much brighter star clearly would make more challenging the observation of Gl 229B spectra (see Oppenheimer et al. 1998a).

The effect of Gl 229A on the stability of the planetary companions around Gl 229B can be estimated using the results of dynamical simulations by Holman & Wiegert (1999), who found a relation for the critical orbital semimajor axis (a_c, i.e., the maximum with stable orbit) as a function of mass ratio, $\mu = m_2/(m_1 + m_2)$, where m_1 is the mass with the planetary system and m_2 is the perturbing body, with the eccentricity e and the orbital semimajor axis a. For the Gl 229 system we have $m_2 = m_{\mathrm{Gl\,229B}} =$ 0.050–0.025 $M_\odot$ and $m_1 = 0.57\ M_\odot$ (Golimowski et al. 1998), i.e., $\mu = 0.92$–0.96. The relation of Holman & Wiegert (1999) is defined for $\mu = 0.1$–0.9; thus application to the Gl 229 system requires an extrapolation. Considering only the case of $\mu = 0.92$ (i.e., $M_{\mathrm{Gl\,229B}} = 0.050\ M_\odot$), we find that equation (1) of Holman & Wiegert (1999) becomes

$$a_c = (0.114 - 0.092e - 0.032e^2)a\ . \tag{8}$$

Figure 3 shows a contour plot of the critical semimajor axis as a function of orbital semimajor axis and eccentricity.

The orbit of Gl 229B around its primary is not yet determined because of the very long period. Golimowski et al. (1998) derived lower limits $a \geq 32$ AU, $e \geq 0.25$, $P \geq 236$ yr on a 1 yr baseline; $a = 32$ AU and $e = 0.25$ would imply $a_c = 2.8$ AU, $a = 44$ AU (the present projected separation) and $e = 0.25$ would imply $a_c = 3.9$ AU, and $a = 32$ AU and $e = 0.5$ would imply $a_c = 1.9$ AU. We conclude that the inner planets as the "scaled" Jupiter satellites are not affected by the presence of Gl 229A whereas a true Jupiter analog (i.e., $a = 5.2$ AU) is likely not allowed to have a stable orbit. If the orbit is highly eccentric ($e > 0.5$ and $a = 32$ AU, worst case), the effects of dynamical interactions would be no longer negligible even for a "scaled" Jupiter ($a = 1.9$ AU).

This discussion applies to the stability of the planets' orbit once they are formed. Another issue concerns the effects of binarity on formation of the planetary system. Recently Rodriguez et al. (1998) showed that the circumstellar disk around the components of the binary system L1551 seems to be truncated at about 10 AU from the stars. The

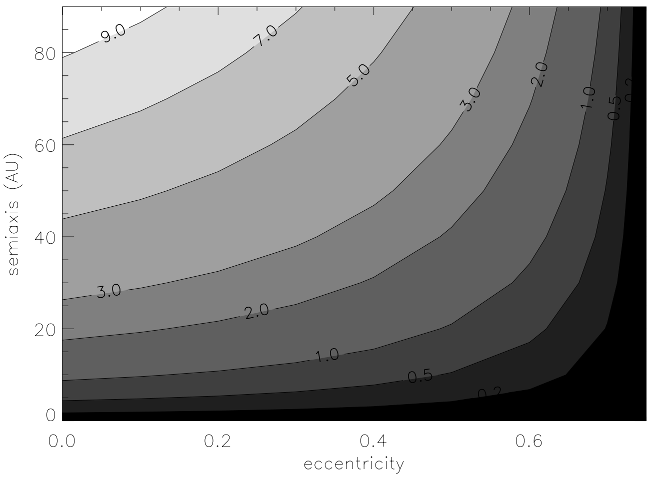

FIG. 3.—Contour plot of critical semimajor axis for stable planets around Gl 229B as a result of the gravitational influence of Gl 229A as a function of orbital semimajor axis and eccentricity.

separation of the components is similar to the Gl 229 system (45 AU).

5. TECHNICAL FEASIBILITY

5.1. Spectral Range

Old BDs such as Gl 229B are very faint at optical wavelengths ($R_{\mathrm{Gl\,229B}} \geq 22$). Thus it is necessary to work at near-infrared (NIR) wavelengths.[5] The spectral distribution of Gl 229B is shown in Figure 4 (from Oppenheimer et al. 1998a).

The most suitable range for RV studies is probably the J band (1.25 μm). Simultaneous spectral coverage of Z, H, and K bands would contribute to a better RV precision provided that a suitable reference spectrum is available (see below).

5.2. Radial Velocity Precision

We showed that the identification of Earth-like planets around BDs such as Gl 229B requires an RV precision of about 1 m s^{-1} in J band. To check if this goal is feasible, we consider the errors on RV determinations due to photon noise, using the following relation (Brown 1990):

$$\delta v \simeq \frac{cw}{\lambda d (N_{\mathrm{pix}} I_c)^{1/2}}\ \mathrm{ms}^{-1}\ , \tag{9}$$

where c is the speed of light, w the width of spectral line, N_{pix} the number of pixels involved in a line, d the line depth as a fraction of the continuum intensity, λ the wavelength, and I_c the continuum intensity. The expression δv represents the error on RV of a single line due to photon noise. It does not include systematic errors.

[5] Cold BDs are brighter in the NIR not only due to the lower temperature. The H_2O absorption makes them 2–10 brighter than the blackbody value at J and H bands. They are enhanced with respect to the blackbody at Z and M bands too. See Burrows et al. (1997) for details.

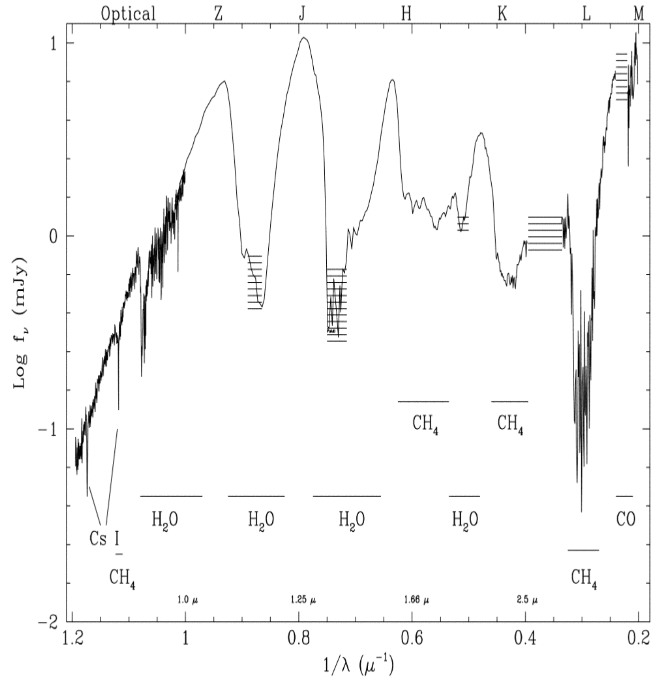

FIG. 4.—Spectrum of Gl 229B from Oppenheimer et al. (1998a)

Two possible values of $v \sin i$, 10 and 20 km s^{-1}, are considered. The rotation broadening (FWHM) reaches 0.07 and 0.14 nm, respectively, at J band (1.25 μm). Thus the rotation broadening would dominate the line profile at high resolution ($R > 20{,}000$). At $R = 100{,}000$ and $R = 150{,}000$ (2 pixel sampling) the line profile will have an FWHM of 11 and 17 pixels, respectively, for $v \sin i = 10$ km s^{-1} and 22 and 34 pixels for $v \sin i = 20$ km s^{-1}. We assume $d = 0.4$ and 0.2 as indicative values of line depth for $v \sin i = 10$ and 20 km s^{-1} respectively (see Gray 1992, Fig. 17.7). Inserting these values, equation (9) becomes

$$\delta v \simeq \frac{12{,}660}{(I_c)^{1/2}} = \frac{12{,}660}{\mathrm{S/N}}\ \mathrm{ms}^{-1} \tag{10}$$

for $R = 100{,}000$, $v \sin i = 10$ km s^{-1};

$$\delta v \simeq \frac{10{,}180}{(I_c)^{1/2}} = \frac{10{,}180}{\mathrm{S/N}}\ \mathrm{ms}^{-1} \tag{11}$$

for $R = 150{,}000$, $v \sin i = 10$ km s^{-1};

$$\delta v \simeq \frac{35{,}030}{(I_c)^{1/2}} = \frac{35{,}030}{\mathrm{S/N}}\ \mathrm{ms}^{-1} \tag{12}$$

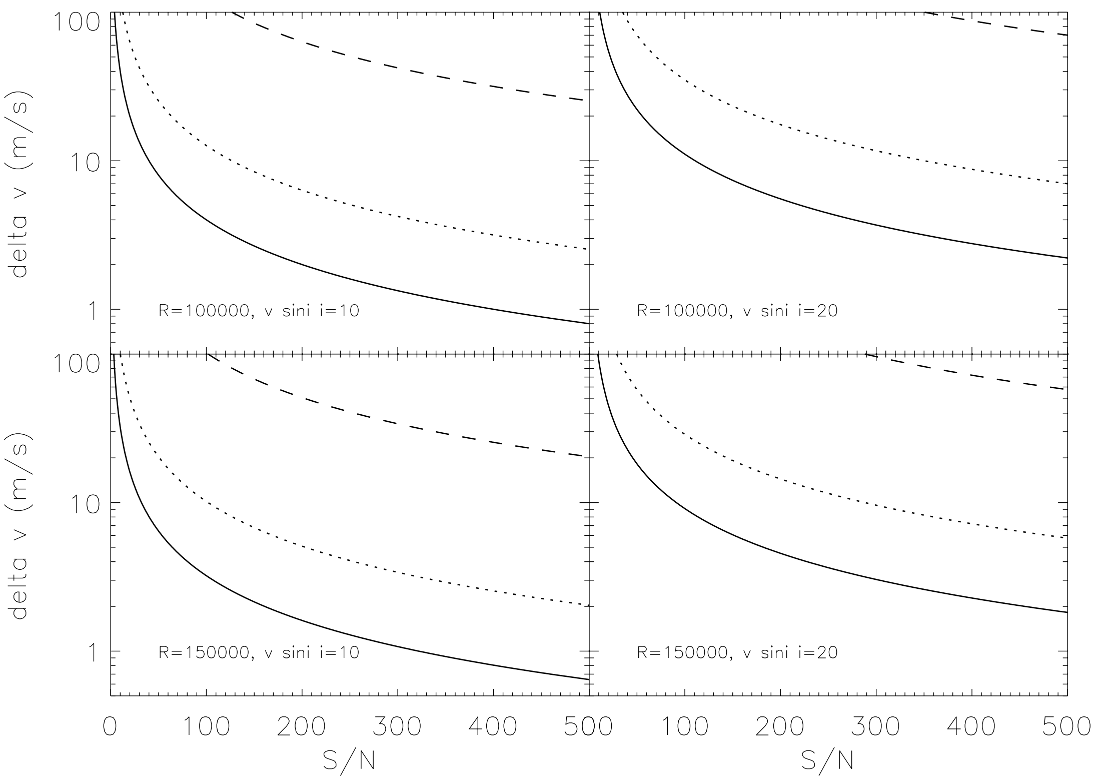

FIG. 5.—Photon noise radial velocity errors as a function of S/N for a combination of rotation broadening of stellar lines and spectrograph resolution. In each panel dashed, dotted, and solid lines represent radial velocity errors for $N_{\text{lines}} = 1$, 100, and 1000, respectively.

for $R = 100{,}000$, $v \sin i = 20 \text{ km s}^{-1}$;

$$\delta v \simeq \frac{28{,}810}{(I_c)^{1/2}} = \frac{28{,}810}{\text{S/N}} \ \ \text{ms}^{-1} \tag{13}$$

for $R = 150{,}000$, $v \sin i = 20 \text{ km s}^{-1}$, where S/N is the signal-to-noise ratio per resolution element.

Considering a simultaneous coverage of many spectral lines (N_{lines}), the photon noise becomes

$$\delta v_N = \frac{\delta v}{\sqrt{N_{\text{lines}}}} \, . \tag{14}$$

The number of observable lines is limited by rotation broadening rather than spectrograph resolution.[6] A conservative estimate (taking into account telluric contamination) is about 100–200 lines, assuming complete coverage of J band. Simultaneous coverage of Z, J, H, and K bands would make it possible to increase N_{lines} up to 500–1000, depending on spectrograph resolution and rotation broadening.[7]

The required RV precision (1 m s^{-1}) is a very challenging goal, and it is likely not feasible if $v \sin i = 20 \text{ km s}^{-1}$ (formally this would require $\text{S/N} = 900$ and $N_{\text{lines}} = 1000$ in an $R = 150{,}000$ spectrograph). If $v \sin i = 10 \text{ km s}^{-1}$, then $\delta v = 1 \text{ m s}^{-1}$ for $\text{S/N} = 320$, $N_{\text{lines}} = 1000$ or $\text{S/N} = 450$, $N_{\text{lines}} = 500$ ($R = 150{,}000$). If $N_{\text{lines}} = 500$ and $v \sin i = 10 \text{ km s}^{-1}$, then $\delta v = 2 \text{ m s}^{-1}$ is reached with $\text{S/N} = 225$, while $\delta v = 10 \text{ m s}^{-1}$ requires $\text{S/N} = 45$.

Figure 5 shows the photon noise–limited RV precision as a function of S/N for $v \sin i = 10$ and 20 km s^{-1} and $R = 100{,}000$ and 150,000.

The error budgets quoted above only concern errors due to photon noise and do not include systematic errors. In the

[6] On the other hand, a spectrum at very high resolution ($R > 100{,}000$) would allow a detailed study of the line profile (and its temporal variations if present) and thus the identification of surface inhomogeneity signatures.

[7] The availability of large-format (2000 × 2000) IR arrays should make easier the design of a cross-dispersed echelle covering a large part of the range 1–2.5 μm. A major issue of such large spectral coverage concerns the availability of a reference spectrum spanning the whole spectral range of interest.

best case they can be as low as 1–2 m s^{-1},[8] using the iodine cell technique and sophisticated data modeling (Butler et al. 1996). Also at NIR wavelengths the reference spectrum can be provided by an absorbing cell. Absorbing cells for IR high-precision RV determinations are at present under study at ESO (G. Wiedemann 1998, private communication). At present an RV precision of 10 m s^{-1} is achieved at Kitt Peak using an N_2O cell (Deming et al. 1987). Thus an NIR RV precision similar to the visible seems feasible. The IR spectrograph CRIRES at the Very Large Telescope (VLT)[9] is conservatively expected to have an RV precision of 10 m s^{-1}, but it could be improved using a full analysis and monitoring of the behavior of the spectrograph (Endl et al. 1999).

A dedicated instrument, optimized for RV studies (stable input beam, no moving parts, large simultaneous spectral coverage) would make it easier to reach the 1 m s^{-1} limit.

5.3. Telescope Size and Exposure Time

The very faint magnitude of Gl 229B clearly requires a very large telescope to reach the S/N required to reach the 1 m s^{-1} RV precision. As a reference we consider the expected performances of CRIRES at VLT (Wiedemann 1997): 50 s to obtain S/N = 100 for a $J = 10$ mag star. Gl 229B has $J = 13.5$. This implies an exposure time of 20 minutes to reach S/N = 100. A 1 hour exposure time leads to S/N = 170 and 2 hr to S/N = 245.

This means that CRIRES would be able to obtain RV determinations of Gl 229B with photon noise errors of 7.5 and 5.2 m s^{-1} (1 and 2 hr exposure time) if $v \sin i = 10$ km s^{-1}, and 20 and 15 m s^{-1} (1 and 2 hr exposure time) if $v \sin i = 20$ km s^{-1}.[10]

Monitoring Gl 229B with a precision of 10 m s^{-1} could reveal planets of 10 $M_\oplus$ within 0.01–0.02 AU and giant planets of 1 M_J up to an orbital radius larger than the critical radius discussed in § 4.3. Moreover, it would be possible to check its intrinsic RV stability at this quite low level. Thus CRIRES can represent a major step in RV studies of BDs.

To reach the precision required to identify Earth-mass planets in inner orbits, it is necessary to increase spectral coverage, resolution, and telescope size. An $R = 150{,}000$ spectrograph, coupled with an adaptive optics system (0″.2) at a 10 m telescope, might reach S/N = 300 (and thus $\delta v = 1.5$ m s^{-1} if $v \sin i = 10$ km s^{-1} and $N_{\rm lines} = 500$) in 1 hr (C. Pernechele 1998, private communication). If systematic errors are kept smaller than 2 m s^{-1}, it would be possible to identify Earth-mass planets near the tidal limit and 10 $M_\oplus$ planets within 0.2–0.5 AU.

6. ADDITIONAL TARGETS

This study indicates the possible feasibility of RV planetary search around the BD Gl 229B using a 10 m class telescope and a specifically designed NIR spectrograph. Main issues concern both its intrinsic properties (RV stability and rotation velocity, unknown at present) and the severe technical requirements (dedicated NIR spectrograph and suitable reference spectrum with large simultaneous spectral coverage).

Clearly monitoring one single target would make low the success probability, even taking into account only the projection effect (i.e., sin *i* factor). However, the possible candidates are not limited to Gl 229B, because the number of identified BDs is continuously growing[11] and is expected to grow more and more with all-sky NIR deep surveys such as DENIS and 2MASS (Delfosse et al. 1997, 1999; Kirkpatrick et al. 1997). The expected number of BDs candidates from these surveys is a few hundred. Clearly in a magnitude-limited survey there should be a strong bias toward more massive and younger BDs, which are intrinsically brighter. Thus only a few (10 or less) Gl 229B analogs (low-mass old BDs) should be detected (Kirkpatrick et al. 1997; Delfosse et al. 1999). However, even the more numerous and slightly more massive BDs ($M \sim 0.06$–$0.07\ M_\odot$) can be good targets for RV planetary searches.

Table 3 reports the parameters of some of the identified candidates or confirmed BDs, thus providing a list of possible targets even slightly more massive and/or younger than Gl 229B. This list should not to be regarded as exhaustive.[12] Some of the BDs listed in Table 3 are significantly fainter than Gl 229B and thus not suitable for the high-resolution work proposed here.

For free-floating BDs such as Kelu 1, direct imaging using the *Hubble Space Telescope* is suitable to put significant upper limits on the presence of giant planets at large orbital radii (Martin et al. 1999). These researches, as well as astrometric monitoring of nearby BDs, represent an ideal

[8] We consider as systematic errors the errors on RV due to spectrograph point-spread function (see Butler et al. 1996). Zero-point errors are larger but unimportant here because we are interested only in RV variations.

[9] The CRyogenic InfraRed Echelle Spectograph (CRIRES) is a high-resolution (up to 100,000) near-infrared (1–5 μm) spectrograph, foreseen to be installed at VLT-UT4 in 2002. See Wiedemann (1997) and the CRIRES Web site (http://www.eso.org/instruments/crires/) for details.

[10] Following Wiedemann (1997), we assume a simultaneous coverage of 100 lines.

[11] Very recently, two field methane BDs (i.e., Gl 229B analogs) were identified (Strauss et al. 1999; Cuby et al. 1999). However, one of them (NTTDF 1205−0744) is 6 mag fainter than Gl 229B, and thus a high-resolution study as proposed here is not feasible for this object.

[12] For a complete census of BDs in the Pleiades and star-forming regions, see Neuhauser et al. (1999).

TABLE 3

IDENTIFIED BROWN DWARFS

Name	I (mag)	J (mag)	K (mag)	T_{eff} (K)	$M/M_{\odot}$	Age (Myr)	Remarks	Reference
Gl 229B	20.0	13.5	13.4	$\sim$900	0.02–0.055	0.5–5	Binary	1
Kelu 1	16.8	13.7	11.79	1900	<0.075	...	Field	2
DENIS J12-15	18.19	14.43	12.73	1600	<0.06	<1	Double BD	3, 4
DENIS J10-15	17.80	14.08	12.71	1800	0.075	3	Field	3
DENIS J02-11	18.30	14.63	13.00	<1500	<0.06	...	Field	3
LP 944-20	14.16	...	9.58	2200	0.06	0.5	Field	5
296A	14.6	...	...	2800	$\sim$0.065	<0.2	Field	6
G196-3B	18.28	14.73	12.49	1800	0.025	0.1	Binary	7
SDSS 1624+00	21.2	15.53	15.70	$\sim$900	0.015–0.060	0.3–5	Field	8
NTTDF 1205−0744	>26	20.15	20.3	$\sim$900	...	...	Field	9
Teide 1	18.80	...	15.11	2600	0.055	0.1	Pleiades	10
Calar 3	18.73	...	14.94	2600	0.055	0.1	Pleiades	10
Roque 25	21.17	...	16.27	...	0.035	0.1	Pleiades	11
RPr 1	21.01	17.7	16.44	...	0.07	0.5	Praesepe	12

REFERENCES.—(1) Nakajima et al. 1995; (2) Ruiz et al. 1997; (3) Delfosse et al. 1997; (4) Martin et al. 1999; (5) Tinney 1998; (6) Thackreh et al. 1997; (7) Rebolo et al. 1998b; (8) Strauss et al. 1999; (9) Cuby et al. 1999; (10) Rebolo et al. 1996; (11) Martin et al. 1998; (12) Magazzú et al. 1998.

complement to RV monitoring, sensible mainly to planets in inner orbits.

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REFERENCES

Bailer-Jones, C. A. L., & Mundt, R. 1999, A&A, 348, 800
Basri, G., & Marcy, G. W. 1995, AJ, 109, 762
Brown, T. 1990, in ASP Conf. Ser. 8, CCDs in Astronomy, ed. G. H. Jacoby (San Francisco: ASP), 335
Burrows, A., et al. 1997, ApJ, 491, 856
Burrows, A., & Liebert, J. 1993, Rev. Mod. Phys., 65, 301
Burrows, A., & Sharp, C. M. 1999, ApJ, 512, 843
Butler, R. P., Marcy, G. W., Williams, E., McCarthy, C., Dosanjh, P., & Vogt, S. S. 1996, PASP, 108, 500
Cuby, J. G., Saracco, P., Moorwood, A. F. M., D'Odorico, S., Lidman, C., Comeron, F. & Spyromilio, J. 1999, A&A, in press
Delfosse, X., et al. 1997, A&A, 327, L25
Delfosse, X., Forveille, T., Mayor, M., Perrier, C., Naef, D., & Queloz, D. 1998, A&A, 338, L67
Delfosse, X., Tinney, C. G., Forveille, T., Epchtein, N., Borsenberger, J., Fouqué, P., Kimeswenger, S., & Tiphene, D. 1999, A&AS, 135, 41
Deming, D., Espenak, F., Jennings, D. E., Brault, J. W., & Wagner, J. 1987, ApJ, 316, 771
Endl, M., Kurster, M., & Els, S. 1999, poster paper presented at VLT Opening Symp., Antofagasta, 1999 March
Golimowski, D. A., Burrows, C. J., Kulkarni, S. R., Oppenheimer, B. R., & Brukardt, R. A. 1998, AJ, 115, 2579
Gray, D. F. 1992, The Observation and Analysis of Stellar Photospheres (Cambridge: Cambridge Univ. Press)
Hillenbrand, L. A., Storm, S. E., Calvet, N., Merrill, K. M., Gatley, I., Makidon, R. B Meyer, M. R., & Skrutskie, M. F. 1998, AJ, 116, 1816
Holman, M. J., & Wiegert, P. A. 1999, AJ, 117, 621
Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. 1993, Icarus, 101, 108
Kirkpatrick, J. D., Beichman, C. A., & Skrutskie, M. F. 1997, ApJ, 476, 311
Leggett, S. K., Toomey, D. W., Geballe, T. R. & Brown, R. H. 1999, ApJ, 517, L139
Magazzú, A., Rebolo, R., Zapatero Osorio, M. R., Martin, L. & Hodgkin, S. T. 1998, ApJ, 497, L47
Marcy, G., & Butler, P. 1998, ARA&A, 36, 57
Marcy, G., Butler, P., Vogt, S., Fischer, D., & Lissauer, J. J. 1998, ApJ, 505, L147
Martin, E. L., Basri, G., Delfosse, X., & Forveille, T. 1997, A&A, 327, L29
Martin, E. L., Basri, G., Zapatero-Osorio, M. R., Rebolo, R., & Garcia Lopez, R. J 1998, ApJ, 507, L41
Martin, E. L., Brandner, W., & Basri, G. 1999, Science, 283, 1718
Mayor, M., & Queloz, D. 1995, Nature, 378, 355
Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R, Golimowski, D. A., Matthews, K., & Durrance, S. T. 1995, Nature, 378, 463
Neuhauser, R., et al. 1999, A&A, 343, 883

Oppenheimer, B. R., Kulkarni, S. R., Matthews, K., & van Kerkwijk, M. H. 1998a, ApJ, 502, 932
Oppenheimer, B. R., Kulkarni, S. R., & Stauffer, J. R. 1998b, preprint (astro-ph/9812091)
Rebolo, R., Martin, L., Basri, G., Marcy, G. W., & Zapatero Osorio, M. R 1996, ApJ, 469, L53
Rebolo, R., Martin, L., & Zapatero Osorio, M. R., eds. 1998a, ASP Conf. Ser. 134, Brown Dwarfs and Extrasolar Planets (San Francisco: ASP)
Rebolo, R., Zapatero Osorio, M. R, Madruga, S., Bejar, V. J. S., Arribas, S., & Licandro, J. 1998b, Science, 282, 1309
Rodriguez, L. F., et al. 1998, Nature, 395, 355
Ruiz, M. T., Leggett, S. K., & Allard, F. 1997, ApJ, 491, L107
Saar, S. H., Butler, R. P., & Marcy, G. W. 1998, ApJ, 498, L153
Saar, S. H., & Donahue, R. A. 1997, ApJ, 485, 319
Strauss, M. A., et al. 1999, ApJ, 522, L61
Terndrup, D. M., Krishnamurthi, A., Pinsonneault, M. H., & Stauffer, J. R. 1999, preprint (astro-ph/9906148)
Thackreh, A., Jones, H., & Hawkins, M. 1997, MNRAS, 284, 507
Tinney, C. G. 1998, MNRAS, 296, L42
———. 1999, Nature, 397, 37
Tinney, C. G., & Reid, I. N. 1998, MNRAS, 301, 1031
Tinney, C. G., & Trolley, A. J. 1999, MNRAS, 304, 119
Wiedemann, G. 1997, CRIRES, ESO/STC, Rep. 211
Wilking, B. A., Greene, T. P., & Meyer, M. R. 1999, AJ, 117, 469