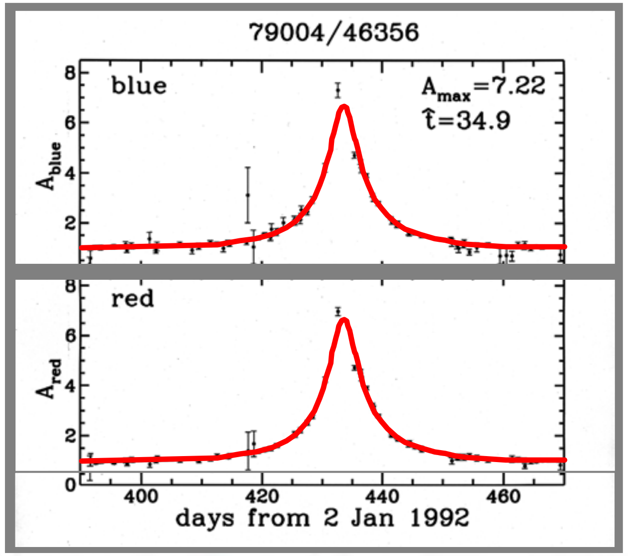
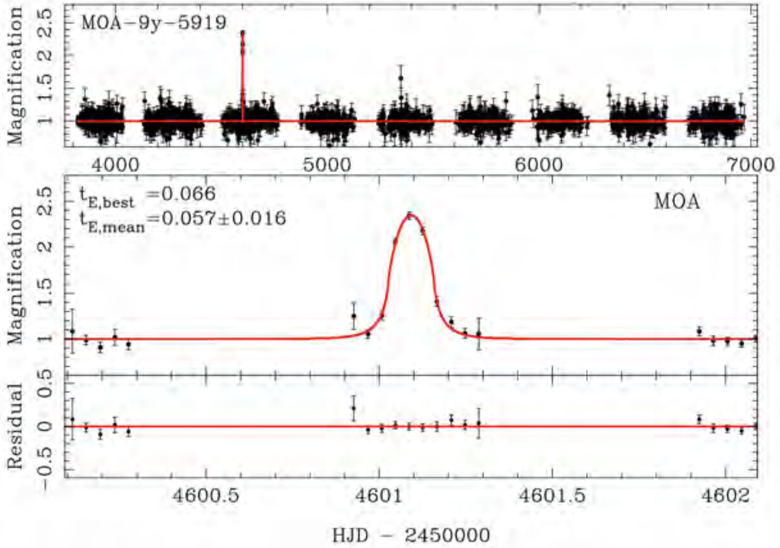
Microlensing's Evolution from Brown Dwarf Dark Mater Search through an "Extragalactic Planet" to the Roman Space Telescope

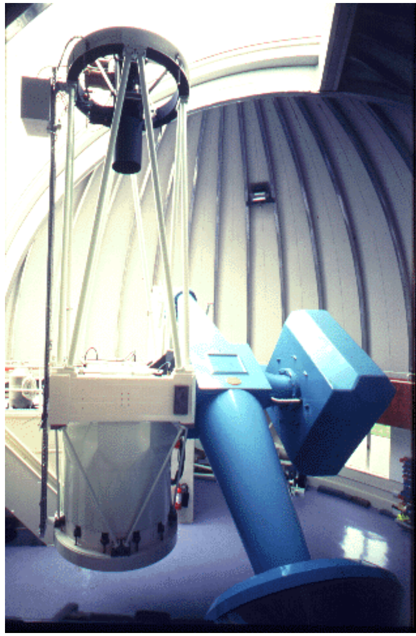
David Bennett

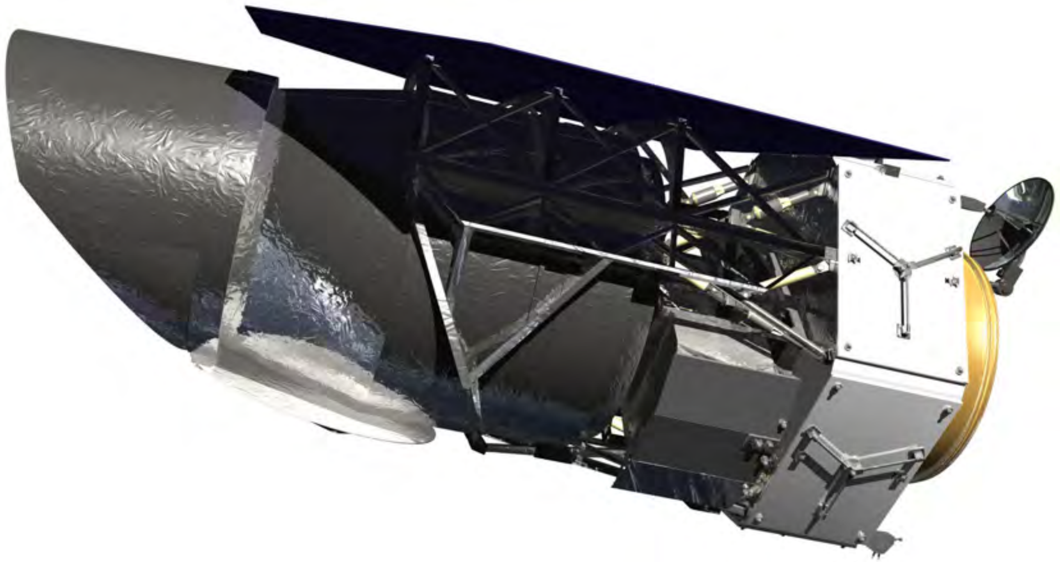
NASA Goddard Space Flight Center

University of Maryland









Bohdan Paczyński 1986

THE ASTROPHYSICAL JOURNAL, 304: 1–5, 1986 May 1

GRAVITATIONAL MICROLENSING BY THE GALACTIC HALO

BOHDAN PACZYŃSKI[1]
Princeton University Observatory
Received 1985 August 1; accepted 1985 October 23

ABSTRACT

The massive halo of our Galaxy has an optical depth to gravitational microlensing $\tau \approx 10^{-6}$. If the halo is made of objects more massive than $\sim 10^{-8}\ M_\odot$, then any star in a nearby galaxy has a probability of 10^{-6} to be strongly microlensed at any time. The lensing events last ~2 hr if a typical "dark halo" object has a mass of $10^{-6}\ M_\odot$, and they last ~2 yr for objects of $100\ M_\odot$. Monitoring the brightness of a few million stars in the Magellanic Clouds over a time scale between 2 hr and 2 yr may lead to a discovery of "dark halo" objects in the mass range 10^{-6}–$10^{2}\ M_\odot$ or it may put strong upper limits on the number of such objects.

Subject headings: galaxies: Magellanic Clouds gravitation — stars: variables

My ignorance of astronomy was the key to my enthusiasm:

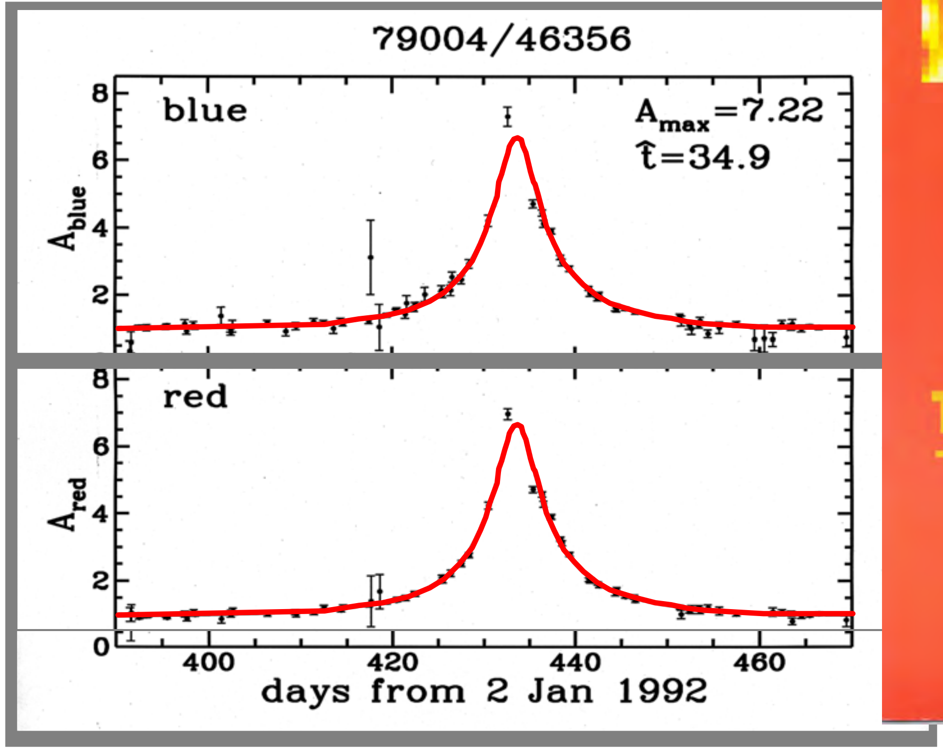
"Dave Bennett was not an astronomer and he did not know that there are all those variable stars that would form a background of 'noise' for the vary rare microlensing events. He did not know that the atmospheric seeing is blurring stellar images in a different way every night. He did not know many other things. The bottom line was: he did not know the project could not be done, and so he tried to persuade me, a seasoned astronomer, that the project was feasible." (Paczynski, arXiv:gr-qc/9409004)

On a visit to Livermore in 1989, I suggested the LMC microlensing project to Charles Alcock

1993: First Microlensing Events

Alcock started the MACHO Project, including me, and the competing French EROS project was started based on a talk given by Alcock. In MACHO, we thought that OGLE was also started in response to discussions between Alcock and Paczyński.

- MACHO: LMC-1 event
  - Nature paper (and cover)
- OGLE: 1st bulge event
  - Acta Astronomica paper
- EROS: 2 microlensing "candidates"
  - (both later retracted)
- Discoveries came in the face of wide-spread skepticism of microlensing

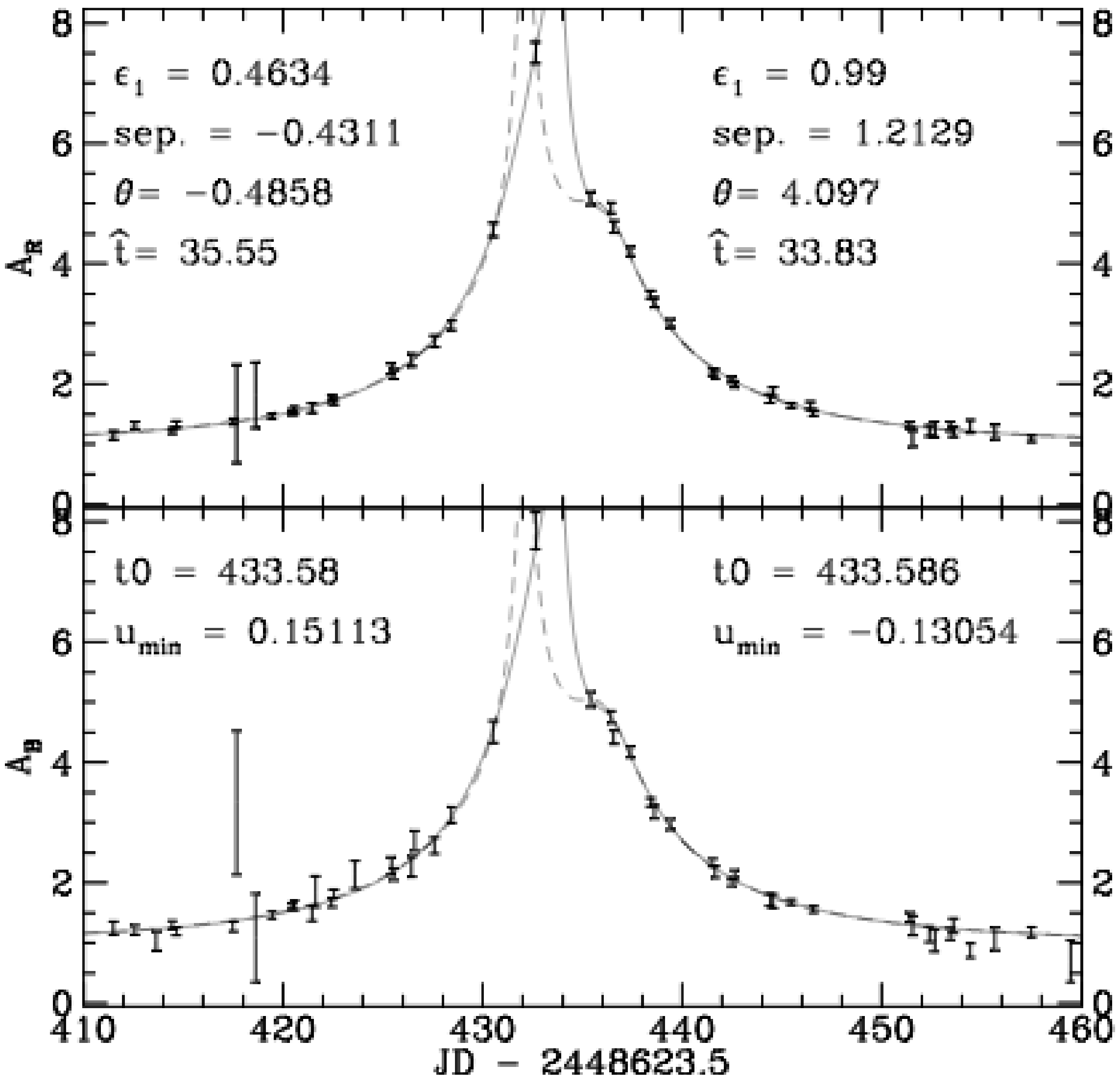


MACHO LMC-1: Extra Galactic Planet?

Sun Hong Rhie in Oct., 1993

Deviation at A ~ 5 is a good fit to a q = 0.01 planetary event, but an equal mass binary (dashed curve) fits nearly as well (Rhie & Bennett 1996).

Also Dominik & Hirshfeld (1994, 1996)



1st International Microlensing Conference
Livermore, CA, January 13-15, 1995

Spurred by a suggestion (or demand)
from Sun Hong Rhie

```
From alcock@sunlight Tue Sep 27 11:13:00 1994
Date: Tue, 27 Sep 94 11:12:46 PDT
From: alcock@sunlight (Charles Alcock)
To: bennett@sojin.llnl.gov, gould@payne.mps.ohio-state.edu,
        kcf@merlin.anu.edu.au, spiro@dphcls.saclay.cea.fr,
        spiro@hep.saclay.cea.fr
Subject: Scientific Organizing Committee

Workshop on Gravitational Microlensing
Scientific Organizing Committee

Ken Freeman (Chair), David Bennett, Andy Gould, Michel Spiro

Dear Ken, David, Michel, & Andy,

This is to start things more formally, for the upcoming workshop.

I am pleased that you have agreed to serve on the Scientific Organizing
Committee for the Workshop on Gravitational Microlensing, which will
be held on January 13 – 15, 1995, in either Livermore or Berkeley. The
exact venue will be determined by the end of next week; this should not
impact your planning.

   ...

Have fun, and please keep me informed regularly of your decisions.

Regards,

Charles
```

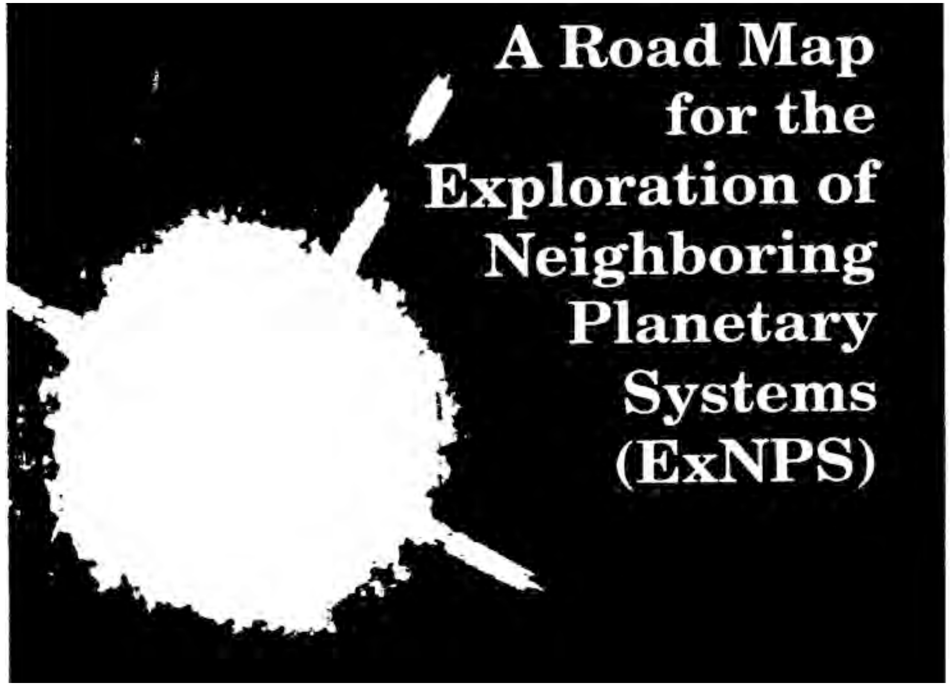
Microlensing as US Priority 1994-5: ExNPS

- Complicated process
  - 3 review teams selected via proposal process – produce 3 reports
  - Merged team with members of all 3 teams writes summary report
  - Blue Ribbon Panel gets summary report and writes their own report
- Members of 3 panels, David Tytler, Stan Peale, and Andy Gould push for a ground-based microlensing program to measure η_{earth}
- Blue Ribbon Panel rejected microlensing program in favor of IR version of Terrestrial Planet Finder

nsing surveys are now finding dozens of star-star micro
ɔer year, and could discover a planet around an ordinary lo
ıe near future. An expanded survey could find hundreds of ı
asses, around hundreds of distant stars in a decade. Micro
ɜrmine the frequency of planets, the star-planet mass ratios,
net separations using standard photometry.

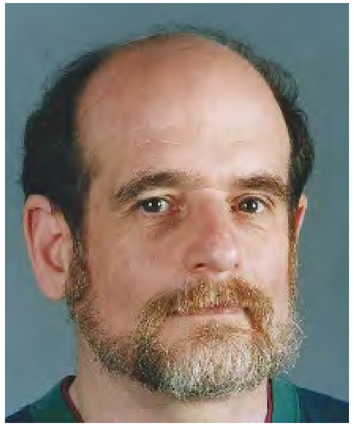
nsing events occur when two distant stars align by cha
" star at ~8 kpc and a "lens" star at 1–7 kpc (Figure 4-11). T
ıses the light from the source producing a typical magnific
ɜs which varies smoothly and predictably as the lens move
connecting the source and the Earth (Figure 4-12).

orbiting the lens star can produce additional magnifi
ıes exceeding 100% which last 1.5–50 hours, depending



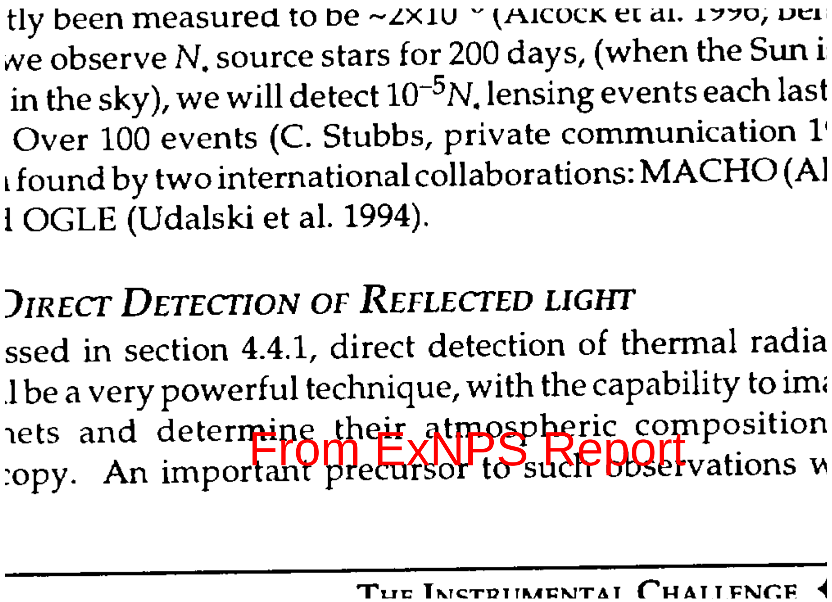

Tytler


Peale


Gould

Bennett & Rhie (1996)

- Ground-based Microlensing vs. FRESIP (early Kepler) to measure η_{earth}
- Tytler pushed for planetary light curves with finite source effects to show microlensing can find Earths
- Bennett & Rhie answer Tytler's call
- ExNPS combined report recommends 4-telescope ground based microlensing program


tly been measured to be ~2x10⁻⁶ (Alcock et al. 1996; Ben
we observe N_* source stars for 200 days, (when the Sun i
in the sky), we will detect $10^{-5}N_*$ lensing events each last
Over 100 events (C. Stubbs, private communication 1
found by two international collaborations: MACHO (Al
OGLE (Udalski et al. 1994).

DIRECT DETECTION OF REFLECTED LIGHT

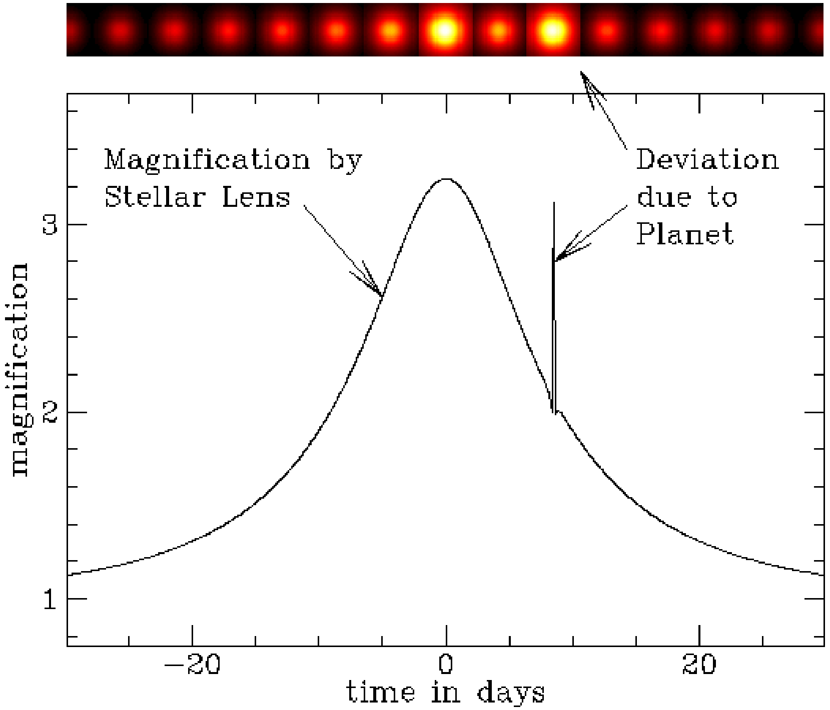
ssed in section 4.4.1, direct detection of thermal radia
l be a very powerful technique, with the capability to ima
nets and determine their atmospheric composition
copy. An important precursor to such observations w

THE INSTRUMENTAL CHALLENGE

From ExNPS Report

Bennett & Rhie

Bennett & Rhie simulation code, using image centered ray shooting became the 1st code capable of modeling planetary microlensing light curves. The code is now named eesunhong (which is Sun Hong Rhie in Korean).



Paczyński 1996 Annual Reviews Article

In early 1996, Paczyński had submitted and Annual Reviews of Astronomy and Astrophysics article that claimed that microlensing was insensitive to Earth-mass planets.

We got him to correct this in the proofs.

Annu. Rev. Astron. Astrophys. 1996. 34:419–59

GRAVITATIONAL MICROLENSING IN THE LOCAL GROUP

Bohdan Paczyński

Princeton University Observatory, Princeton, New Jersey 08544-1001

```
From bp@astro.Princeton.EDU Thu Feb 22 16:49:04 1996 (PST)
From: Bohdan Paczynski <bp@astro.Princeton.EDU>
Date: Thu, 22 Feb 1996 19:48:51 -0500
To: bennett@beowulf.llnl.gov
Subject: Re:  plots to follow

Dear Dave,

Thanks a lot for lots of most interesting plots.  It looks I was very wrong
with my estimate of a vely low amplitude of planetary events.  I have
displaced somewhare your and Rhie's paper on planetary lensing and cannot
find it.  Can you e-mail me a copy?   Thanks, now I have to digest
your figures,

Bohdan
```

```
From bp@astro.Princeton.EDU Sat Feb 24 05:31:24 1996 (PST)
From: Bohdan Paczynski <bp@astro.Princeton.EDU>
Date: Sat, 24 Feb 1996 08:28:59 -0500
To: bennett@beowulf.llnl.gov
Subject: Re:  Bohdan's criticism

Dear Dave,

I was very dumb last fall while writting the current draft of my review.
As I have not head the proofs yet, I plan to modify the section on planets,
following (and acknowledging) the information and insight I got independently
from you and from Jordi Miralda-Escude ...

Best wishes,   Bohdan
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THE ASTROPHYSICAL JOURNAL, 472:660–664, 1996 December 1

DETECTING EARTH-MASS PLANETS WITH GRAVITATIONAL MICROLENSING

DAVID P. BENNETT[1,2] AND SUN HONG RHIE[1]
Received 1996 April 9; accepted 1996 June 25

Backlash from FRESIP (soon to be Kepler)

- In response to ExNPS study, the FRESIP team launched a 1-year attack on microlensing planet searches
- Bill Cochran's memo from June, 1995
  - Concludes: "the fatal flaw of a microlensing planetary search program" You get no useful information beyond the existence of the planet and a guess at the mass."
- A few months before the discovery of 51 Peg b
  - Planets that are easy to detect via transits made the case for Kepler much stronger
- Attack abandoned after ~1 year

The University of Texas at Austin
McDonald Observatory and Astronomy Department

MEMORANDUM

June 19, 1995

To: FRESIP Team

From: Bill Cochran

Subject: Gravitational Microlensing

1 A Short Primer on Gravitational Lensing

The physics and applications of gravitational lensing are described in detail in the book "Gravitational Lenses" by P. Schneider, J. Ehlers, and E. E. Falco (Springer-Verlag, 1992). Lensing results simply from the gravitational deflection of light as it passes a body. The deflecting body does not act as a lens in the true optical sense, since it does not focus the source into a discrete image at some particular distance. In the discussion below, we will present a simplified introduction to gravitational lensing for the non-expert. We will develop the concepts necessary to understand lensing, but will neglect many of the messy details (such as finite size of the source and lens). To follow the development in the Schneider, Ehlers and Falco book, when light passes a body at an impact parameter ξ much larger than the Schwarzschild radius $R_s = 2GM/c^2$, the light will be deflected by the "Einstein angle",

$$\hat{\alpha} = \frac{4GM}{c^2\xi} = \frac{2R_s}{\xi} \quad .$$

If we follow standard convention and denote the distance from the observer to the source as D_s, the distance from the observer to the intervening deflecting (lensing) mass as D_d, and the distance from the source to the deflector as D_{ds}, then the geometry of the lensing gives

$$\beta D_s = \frac{D_s}{D_d}\xi - \frac{2R_s}{\xi}D_{ds} \quad ,$$

where β is the true angular separation of the source from the deflector (i.e. the separation which would be observed in the absence of lensing). If we let $\theta = \xi/D_d$ (θ is the angular separation between the deflecting mass and the deflected ray, or the angular impact parameter), then we can derive a lens equation of the form:

$$\beta = \theta - 2R_s\frac{D_{ds}}{D_d D_s} \quad .$$

¿From this, we see that lensing involves a characteristic angle

$$\alpha_0 = \sqrt{2R_s\frac{D_{ds}}{D_d D_s}} \quad ,$$

Ground-based confusion, space-based resolution

Thanks, Blue Ribbon Panel!

- HST images in the late 1990s revealed blending of bulge main sequence stars
- High Angular Resolution needed for precise photometry at low magnification
- Space observations needed for sensitivity at a range of separations and mass determinations

NANCY GRACE ROMAN SPACE TELESCOPE

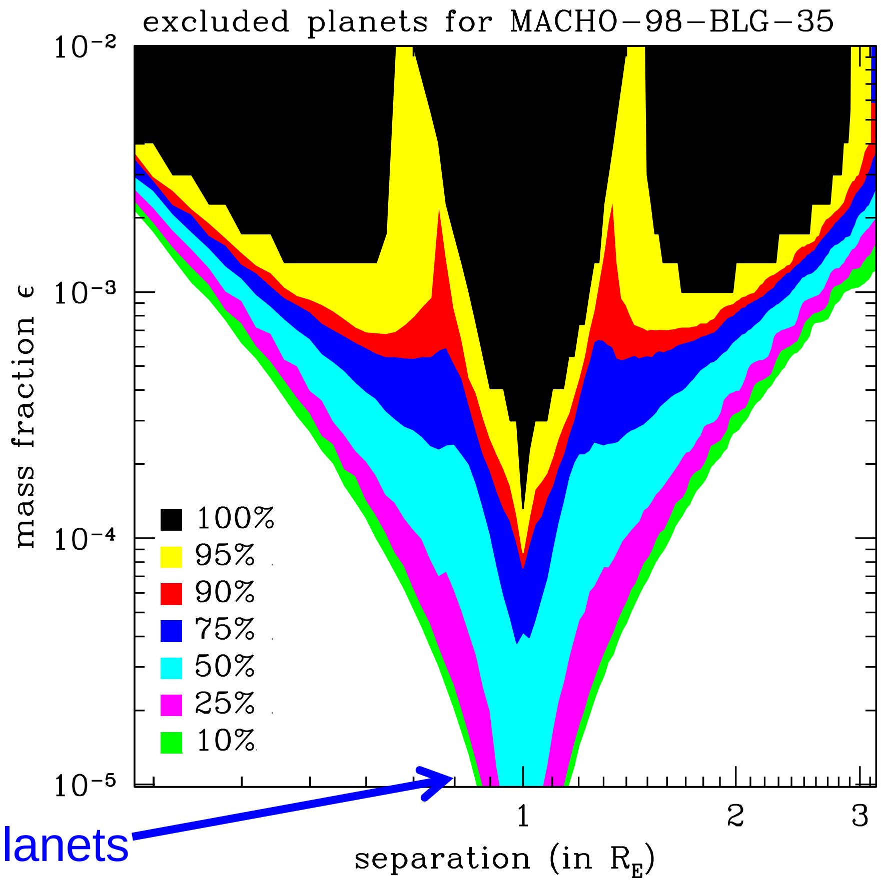
Microlensing Planet Search: MACHO-98-BLG-35

THE ASTROPHYSICAL JOURNAL, 533:378–391, 2000 April 10

ON PLANETARY COMPANIONS TO THE MACHO 98-BLG-35 MICROLENS STAR

S. H. RHIE,[1] D. P. BENNETT,[1,2] A. C. BECKER,[2,3] B. A. PETERSON,[4] P. C. FRAGILE,[1] B. R. JOHNSON,[5] J. L. QUINN,[1] A. CROUCH,[6] J. GRAY,[6] L. KING,[1] B. MESSENGER,[6] AND S. THOMSON[6]
(THE MICROLENSING PLANET SEARCH COLLABORATION)
AND
I. A. BOND,[7,8] F. ABE,[9] B. S. CARTER,[10] R. J. DODD,[7,10,11] J. B. HEARNSHAW,[8] M. HONDA,[12] J. JUGAKU,[13] S. KABE,[14] P. M. KILMARTIN,[7,8] B. S. KORIBALSKI,[15] K. MASUDA,[9] Y. MATSUBARA,[9] Y. MURAKI,[9] T. NAKAMURA,[16] G. R. NANKIVELL,[10] S. NODA,[9] N. J. RATTENBURY,[7] M. REID,[11,10] N. J. RUMSEY,[10] TO. SAITO,[17] H. SATO,[16] S. SATO,[18] M. SEKIGUCHI,[12] D. J. SULLIVAN,[11] T. SUMI,[9] Y. WATASE,[14] T. YANAGISAWA,[9] P. C. M. YOCK,[7] AND M. YOSHIZAWA[19]
(THE MOA COLLABORATION)
Received 1999 May 17; accepted 1999 November 16

- 1st high-mag event and first limits on planets in a microlensing event by MPS & MOA
- Showed some sensitivity to Earth-mass planets
- Demonstrated high sensitivity of high-mag events as predicted by Griest & Safizadeh (1998) (A_{max} > 20)
- **Inspired MOA to focus on exoplanets; helped to inspire μFUN strategy**

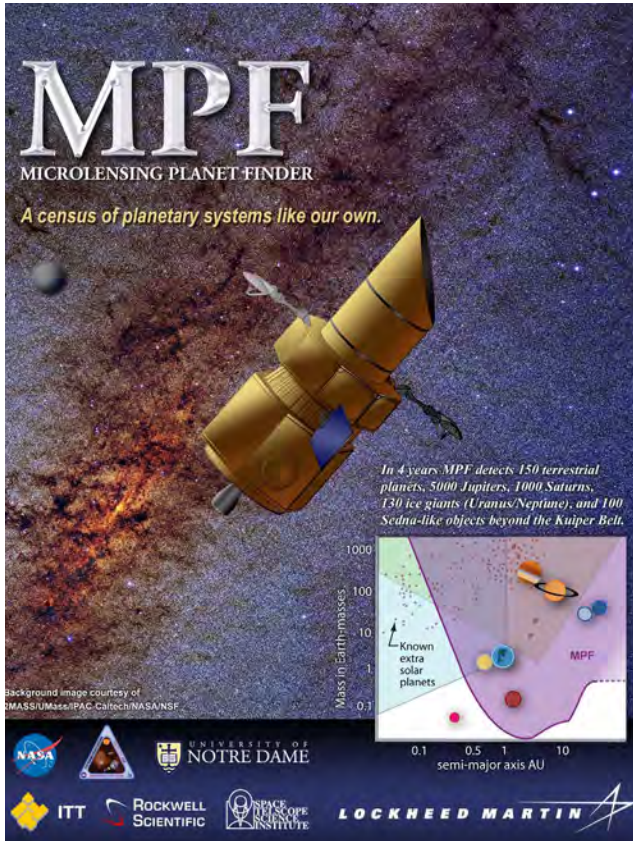


Some sensitivity to Earth-mass planets

NASA Proposals: GEST → MPF → WFIRST → Roman

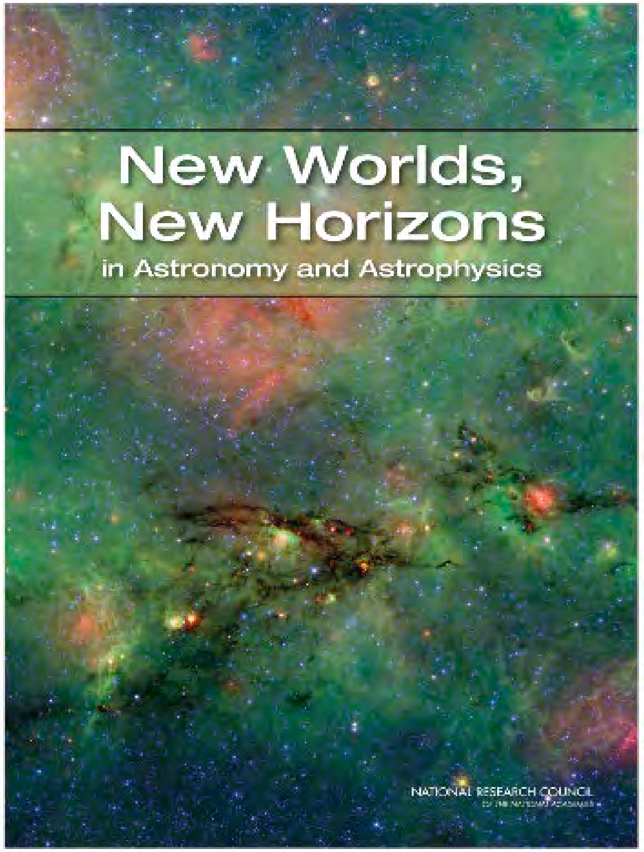
Galactic Exoplanet Survey Telescope (GEST)

- Large CCD focal plane
- Discovery proposal in 2000, MidEx proposal w/ dark energy program in 2001



Microlensing Planet Finder (MPF)

- Large IR detector focal plane
- Discovery Proposals in 2004, 2006, Decadal Survey 2010



Astro2010 Decadal Survey Top Recommendation:
MPF + JDEMΩ + NIRSS = WFIRST

→ Nancy Grace Roman Space Telescope

Sun's Contributions were Celebrated at the Microlensing 18 Meeting

Sun Hong Rhie suffered from Schizophrenia and could not participate in WFIRST/Roman. She died in October 2013.

Santa Barbara, CA, January 20-23rd, 2014

Special Session The Life and Work of Sun Hong Rhie

David Bennett Sun Hong Rhie's Contributions to Exoplanetary Microlensing and a Space-based Microlensing Survey [PPTX]

Phil Yock Remembering the work of Sun Hong Rhie [PDF]

Dmitry Khavinson The fundamental theorem of algebra and a problem in gravitational lensing. S.-H. Rhie's work [PDF]

17:30 *End of Session* **Conference dinner at LCOGT** 18:00 Bus departs from Canary Hotel