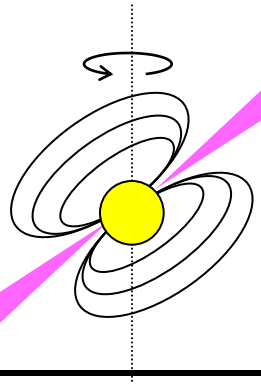
Gravitational Waves, Neutron Stars, and Binary Pulsars

J H Taylor

XXVII Texas Symposium
on Relativistic Astrophysics
December 9, 2013



Princeton University

Overview

- Three inter-related topics: **GW**, **NS**, **BP**, traced (mostly) through these Texas Symposia
- Historical, personal, anecdotal, incomplete, superficial ...
- Emphasis on earlier years: < 1980
- Brief updates on 2013 status

BTS (Before Texas Symposia) Era

Gravitational Radiation

1915: Einstein publishes General Relativity

1916: **GW** from a spinning rod

1918: The "quadrupole formula"

1922: Eddington re-derives quadrupole formula

1936-7: Einstein-Rosen paper (do **GW** exist??)

(D. Kennefick 2007: *Travelling at the Speed of Thought*)

1955, **1957**: Conferences in Berne, Chapel Hill

1960: J. Weber: "time for new-generation experiments"

BTS (Before Texas Symposia) Era

Neutron Stars

1932: Chadwick – discovery of neutron

1934: Baade & Zwicky – *"With all reserve we advance the view that a supernova represents the transition of an ordinary star into a new form of star, the **neutron star**, ..."* .

"In the supernova process mass in bulk is annihilated."

1939: Oppenheimer & Volkoff – structure of **NS**

1962: Giacconi *et al.* discover Scorpius X-1

BTS (Before Texas Symposia) Era

Binary Pulsars

Pulsar? What's that ???

BTS Era
State of Non-optical Astronomies

- **Radio**:

  - One spectral line, $\lambda = 21$ cm
  - No quasars, pulsars, radio stars, CMB, AGN, plerions, molecular clouds, radio jets, interstellar masers, black holes, . . .
  - Main goals: galactic HI mapping; source counts, cosmology via "log N – log S"

- **X-rays**: Sun detected in 1949; plans for new rocket-borne detectors

- **Gamma-rays**: Explorer 11 under development

TS 1: December 1963, Dallas

- Attendance > 250
- Principal topics: Quasi-Stellar Radio Sources & Gravitational Collapse
- Radio, optical obs of QSOs; attempts to explain enormous energies
- R Kerr – rotating black hole
- **NS**: papers by E. Salpeter, H-Y Chiu, L. Gratton
- **GW**: Super-massive stars, grav rad'n during collapse?

TS 2: December 1964, Austin

- Attendance ≈ 400, 21 countries
- Continued discussion of QSOs
  (N = 9, max z = 2.01)
- Radio, x-ray, gamma-ray, cosmic ray obs
- R Davis – building solar neutrino expt
- **NS**: new x-ray sources; H Friedman suggests connection with supernovae
- **GW**: R Sachs – suggests spherical galaxies may appear elliptical (“rippled spacetime”)

TS 3: January 1967, New York

- Attendance ≈ 600
- QSOs: identification, spectra, redshifts, structure, variability, origin . . .

  (100 < N < 200 !! max z = 2.2)
- "Background Radiation" (CMB)

  6 measurements available
- X-ray, gamma-ray, neutrino, cosmic ray obs
- R Dicke – importance of solar oblateness
- Closing panel: *observational* cosmology

TS 3: Jan 1967, NY - cont'd

- **NS**: nothing ...
- **GW**: two theory papers
- Published summary of meeting:
  - papers "speculative or devoid of stringency"
  - "much too many of them"
  - "This is not a critique, but a statement."

A.M.

TS 4: December 1968, Dallas

"Pulsars are the new stars on the screen"

(I. Robinson)

- N = 23, and climbing . . .
- probably **NS** or WD
- could be pulsation or rotation
- Gold: spinning, magnetized **NS**
- Woltjer agrees; says **GW** important at formation
- Pacini, Gunn – energy loss by rotating mag dipole
- Shklovsky: $N_G = 10^5$, birth rate 1/100 yr;
  [also, Scorpius X-1 is a **NS** !]

TS 4: Dec 1968, Dallas - cont'd

Gravitation – New Experiments!

- Dicke – solar oblateness 5×10^{-5} !

  (much discussion...)
- Shapiro – excess radar time delay to Mercury, Venus ("4th test of GR")
- Earth as **GW** antenna: negative result
- Weber – coincidence events between UMd and Argonne (**GW** pulses ?)

TS 5: December 1970, Austin

Summary report:

- "Pulsars are... a traditional topic of Texas Symposia"
- **NS** - T Gold: energy source, emission mechanism
  - H Bethe: equation of state at high densities
  - M Ruderman: crystalline crust, superfluid interior
- About half of conference devoted to gravitation theory or experiment

TS 5: Dec 1970, Austin - cont'd

Gravitational Radiation

J Weber: detection of **GW** pulses !!

- Coincidences, UMd / Argonne, several per day !
- Many statistical tests described
- No correlations found with seismic records, radio pulses, cosmic rays
- Correlated with sidereal time (galactic center direction)
- Weber honored with prize from Babson Gravity Research Foundation
- Discussion papers by M J Rees, J V Jelley . . .

TS 6: December 1972, New York

- Attendance > 1000 !
- Experiment – quasars, pulsars, X-ray sources, **GW**, **NS**
- Theory – naked singularities, black holes, pulsar electrodynamics, **GW, NS**
- "… stormy development in Relativistic Astrophysics during the last few years." -- published summary in *GRG*
- Major disagreements:
  - Quasar redshifts (Woltjer / Arp)
  - **GW** pulses (Weber / Tyson)

TS 7: December 1974, Dallas

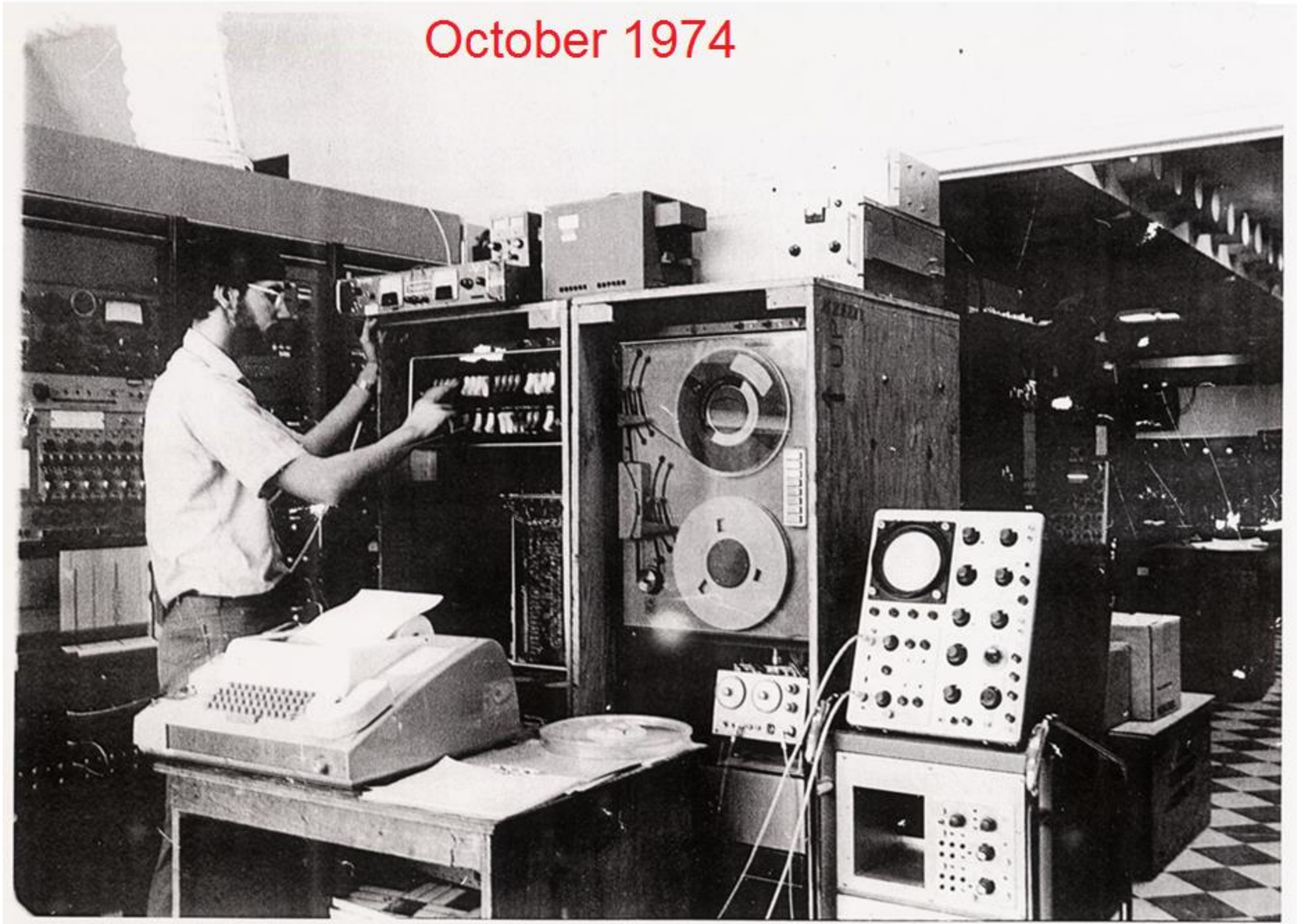
- Attendance > 500
- S Hawking: “Black Holes are White Hot”
- From Vela satellites: Gamma-ray bursts
- **NS:** *many* papers on X-ray sources
- **GW:** S Teukolsky – “**GW** and Black Holes”
- **BP:** B Paczynzki – evolution of close binaries

  JHT – Hulse & Taylor pulsar survey at Arecibo

  (discovery of PSR B1913+16)

R. A. Hulse in Arecibo Control Room

October 1974



PSR B1913+16

- P = 59 ms, P_b = 7.75 hr, e = 0.615
- Size of orbit ≈ solar radius; no eclipses
- Max orbital velocity ≈ 10^{-3} c
- Advance of periastron $\dot{\omega}$ ≈ 4 deg/yr
- Unseen companion: WD or **NS**, mass comparable to pulsar
- $O(v/c)^2$ effects will be easily measurable
- Measure orbital decay via **GW** in ≈ 5 years ?
- After hours at TS 7: R Blandford shows JHT how to fit **BP** timing data

UTD

THE UNIVERSITY OF TEXAS AT DALLAS

11 February 1975

Dr. J. H. Taylor
Department of Physics and Astronomy
University of Massachusetts
Amherst, Massachusetts 01002

Dear Dr. Taylor:

It was a great pleasure for me to meet you at the Seventh Texas Symposium on Relativistic Astrophysics in Dallas. As you know the proceedings of the Symposium will be published as a special issue of the Annals of the New York Academy of Sciences. Unfortunately, until now neither me nor the editor have received your paper. The deadline for manuscripts is long over but I agreed with the publisher to accept a few additional papers. Accordingly, I would be pleased to receive your paper not later than February 25 in order to be able to include it in the Proceedings.

Thank you very much for your cooperation.

Sincerely yours,

Ervin J. Fenyves

"The deadline for manuscripts is long over but I agreed with the publisher to accept a few additional papers"

TS 8: December 1976, Boston

- **BP**: Many papers on evolution of close binaries
- **NS**: many papers, most relating to X-ray sources
- **GW**: W Burke: gravitational radiation damping

  A Rosenblum: energy loss in scattering problems
- Quantum theory in strong gravity

TS 9: December 1978, Munich

- **GW:** E Amaldi – workshop on GW detectors
- **NS:** pulsar emission mechanisms; Crab nebula
- J Ehlers – *"Isolated Systems in General Relativity"*
- **BP:** J Taylor, P McCulloch: *"Evidence for the Existence of Gravitational Radiation . . ."*

PSR B1913+16 – Dec 1978

Keplerian parameters measured with 5 or more significant digits

"Post-Keplerian" parameters:

$\dot{\omega} = 4.226 \pm 0.002$ deg/yr

$\gamma = 4.7 \pm 0.7$ ms

$dP_b/dt = (-3.2 \pm 0.6) \times 10^{-12}$

"We conclude that the most straightforward interpretation… is that gravitational waves exist and carry energy… at a rate consistent with… general relativity."

Quadrupole Formula Controversy

How much mathematical rigor ?

Feynman: Chapel Hill (1957) quotation

PM63: "The question has been raised, whether the energy so calculated has any physical meaning. We shall not concern ourselves with this question here…"

TS 9, 1978: vigorous debate still underway

≈ **1983**: problem essentially settled. (Walker & Will, T Damour, J Anderson, …)

30 Years Later: Pulsars in 2013

- PSRs: N > 2300
- Millisecond PSRs: N > 260
- Binaries (**BP**): N > 220
  - Most have WD companions, e ≈ 0
  - 8 with main-sequence companions
  - 9 NS-NS pairs (generally large e)
  - post-Keplerian effects measurable in most
  - 4 measurements of orbital decay → **GW**

Binary and Millisecond Pulsars

High-precision pulsar timing and **GW**

- Now 4 measurements of orbital decay: 0.3%, 1.4%, 3%, 6% agreement with GR
- Many measurements of $dP_b/dt \approx 0$, also in agreement with GR
- A handful of tests based on other PK params
- Pulsar Timing Arrays: aim to detect nHz **GW**