The Physics of Interstellar

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25 January 2016
Outline

- Einstein, Thorne, and Guiding Principles
- Established Phenomena
- Interstellar’s Phenomena
- Conclusions and the Future
Albert Einstein

- 1905 – Brownian Motion, Photoelectric Effect, Special Relativity (Annus Mirabilis)
- 1907 – Specific Heats
- 1907-1915 – General Relativity
- 1921 – Nobel Prize
- 1924 – Bose-Einstein Statistics
- 1931 – Cosmological Constant
- 1940 – Einstein-Szilárd Letter
- 1955 – Russell-Einstein Manifesto
Kip Thorne

- Theorist at CalTech
  - General Relativity / Cosmology
- Co-founded LIGO (more later)
- Science advisor for Interstellar
  - The Science of Interstellar (2015)

Two Guidelines
- “Nothing would violate established physical laws”
- “All the wild speculations... would spring from science”
“What I maintain, and what I believe [Christopher Nolan] would maintain as well, is that to a very great extent real science can give rise to wonderful ideas for a film that can in most cases be better than what was created from whole cloth out of the brain of a screenwriter..... Real science can be an absolutely fabulous foundation for great filmmaking.”

-Kip Thorne
Science (and) Fiction

- No violations, much speculation
  - Could be true
  - Could be untrue
- Will be careful to distinguish the known from the unknown
- Follow evolution of modern cosmology for guidance
- More research needed!
Outline

- Einstein, Thorne, and Guiding Principles
- Established Phenomena
  - Classical Mechanics
  - Special Relativity
  - General Relativity
  - *Interstellar’s* Phenomena
- Conclusions and the Future
Physics 101: Newtonian Dynamics

- Understanding of the “normal” world
- Mathematically grounded, highly accurate
- Three laws
- Time is absolute and separate from space
Newtonian Gravity

- Explains wide variety of motion
  - Projectile (falling apples)
  - Planetary (Kepler’s Laws)
- Got us to the moon
- *Interstellar* features Martian slingshot (52:30)
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- **Established Phenomena**
  - Classical Mechanics
  - **Special Relativity**
  - General Relativity
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Special Relativity

- Matches all experiments
- Fine tunes Newton’s Laws
- For fast things
  - Subatomic particles
  - Hafele-Keating
- Two “harmless” principles
  - Laws of physics hold for everyone
  - Everyone measures same speed of light
Consequences

- 4D Spacetime
  - Time is a dimension
  - Same as x, y, or z
  - All linked together
- Speed of light is universal speed limit
- Simultaneity is lost
- Mass is a form of energy ($E = mc^2$)
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- Einstein, Thorne, and Guiding Principles
- **Established Phenomena**
  - Classical Mechanics
  - Special Relativity
  - **General Relativity**
    - Gravitational Lensing
    - Time Dilation
    - Gravitational Waves
    - Black Holes
- *Interstellar’s Phenomena*
- Conclusions and the Future
“Hmm... Why is that?”

- Equivalence principle
- Inertial mass = gravitational mass
- Einstein's *gendanken*
- Gravity looks identical to a “space elevator”
General Relativity

- Expansion of special relativity
- Modern understanding of gravity
- Matches every astronomical observation
- Incompatible with Quantum Mechanics
\[ W \left[ \frac{\xi}{\alpha} \left( \frac{\partial f}{\partial t} - \beta \frac{\partial f}{\partial r} \right) + \frac{v}{\phi^2} \frac{\partial f}{\partial r} \right] - \frac{\epsilon W^3}{r \alpha \phi^3} \frac{\partial f}{\partial \varepsilon} \]
\times \left[ \beta \phi^3 \left( - \psi - r \mu \frac{\partial v_r}{\partial r} \right) + v^2 \phi \left( \beta \phi \left( 2r \frac{\partial \phi}{\partial r} - \psi \phi \right) \right) \right.
\left. + r \left( - \mu \frac{\partial \alpha}{\partial r} + \mu^2 \phi^2 \frac{\partial \beta r}{\partial r} - \frac{\partial \phi}{\partial t} \right) \right]
\left. + v_r^3 \left[ r \mu \phi \left( - \mu \frac{\partial \alpha}{\partial r} + \frac{\partial \beta r}{\partial r} - \frac{\partial \phi}{\partial t} \right) - \psi \frac{\alpha}{\phi} \frac{\partial r \phi}{\partial r} \right] \right]
\left. + \phi \left[ r \mu \left( \mu \alpha \frac{\partial v_r}{\partial r} + \frac{\partial \alpha}{\partial r} + \phi^2 \left( - \mu \frac{\partial \beta r}{\partial r} + \frac{\partial v_r}{\partial t} \right) \right) \right.
\left. + r \frac{\partial \phi}{\partial t} - r \beta r \frac{\partial \phi}{\partial r} \right] + v_r \alpha \left[ \frac{\partial \phi}{\partial r} + \psi + \mu \frac{\partial v_r}{\partial r} \right] \right]
\left. + 2r \psi \frac{\partial \phi}{\partial r} + \phi^2 \left( \mu \frac{\partial v_r}{\partial t} - \frac{\partial \beta r}{\partial t} \right) + \frac{\partial \phi}{\partial t} \right] \}
\left[ W^3(1 - \mu^2) \frac{\partial f}{\partial \mu} \left\{ \alpha \left[ \phi \left( \frac{\xi}{W^2} - rv \frac{\partial v_r}{\partial r} \right) + 2r \frac{\xi}{W^2} \frac{\partial \phi}{\partial r} \right] \right.
\right.
\left. + \phi \left[ \beta \phi^2 \left( r \xi \frac{\partial v_r}{\partial r} - \frac{v}{W^2} \right) - \frac{r}{W^2} \left( \xi \frac{\partial \alpha}{\partial r} - \nu \phi^2 \frac{\partial \beta r}{\partial r} \right) \right.
\left. - r \xi \phi^2 \frac{\partial v_r}{\partial t} \right] \right) \}
\right] = \mathcal{C}[f], \quad (26)
Qualitative Analysis

- Space-time is curved by mass
- Imagine the surface of a trampoline
Mass and Curvature

- Standing on the trampoline curves its surface
- Curvature is proportional to mass
Bent Paths

- Tennis ball's path across trampoline would bend
- Bending is due to curvature
- More mass, more bending
Gravitational Lensing
Gravitational Lensing
Gravitational fields also warp time
Clocks run slower near large masses
GPS systems must account for this effect
Gravitational Waves...

- Gravitational radiation
- Ripples in Spacetime
- Hulse and Taylor
  - Binary star system with decaying orbits
  - Indirect evidence
  - Nobel Prize 1993
YES!

- Announced February 11, 2016
- Laser Interferometer Gravitational-wave Observatory (LIGO)
- Echoes classic Michelson-Morley
  - Validated Special Relativity
Black Holes

- Schwarzchild (1916)
- Stephen Hawking vs. Kip Thorne (1971)
  - Scientific wager over Cygnus X-1
  - Conceded bet (1990)
Stellar Progenitors

- Stars are nuclear fusion reactors
- Hydrogen burned into helium
- Gravity vs. fusion
- Stable balance until star runs low on hydrogen fuel
Not with a whimper...

- Star collapses, then supernova
- Flings outer shell into space
- Core remnant is ultra dense
- Black hole created if over 3x sun's mass

The Crab Nebula
Outer Structure

- Accretion disk
  - Flat “food” spiral
  - Extremely hot
  - Emits X-rays
- Relativistic jets
  - Powerful
  - Plasma
  - Polar
**Interior Properties**

- Gravitational singularity
  - Infinite curvature
- Even light cannot escape
- Event horizon is point of no return
Tidal Forces

- Same as moon’s effect on oceans
- Relative strength difference
- Stretched and squeezed
- Spaghettification
Types of Black Holes

- Classify by size
  - Stellar
    - 5-100x sun's mass
    - Act like stars
  - Supermassive
    - Quasars
    - Millions of times bigger than sun
    - Galactic centers
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- Einstein, Thorne, and Guiding Principles
- Established Phenomena
- *Interstellar’s Phenomena*
  - Gargantua
  - Miller’s Planet
  - Wormholes
  - Gravitational Anomalies
  - Higher Dimensions
- Conclusions and the Future
Gargantua

- Mostly real
- Spinning at near speed of light
  - No spaghettification
- Not accreting
  - Unobserved
  - Disk is visible
  - Doesn’t fry astronauts

1:05:45 – 1:06:15
2:13:15 – 2:13:45
Actual Discoveries!

- Gargantuan graphics
  - Double Negative (Inception)
- Couldn’t use ray tracing
  - Gravitational lensing
  - Equations by Kip Thorne
- Wrote new renderer
  - Frames took >100 hours
  - Nearly 800 TB of data
- Two published articles
Time Dilation

- Real!
- Close to Gargantua
- One hour there is seven years
- Science drives drama

1:02:00 – 1:03:20
1:17:30 – 1:18:00
Tidal Waves

- Plausible
- Actually due to tides (vs. tsunami)
- Tidal bore
- Liquid and solid surfaces deformed by tidal forces
- Surfaces misalign

1:10:00 – 1:13:00
The Bulk

- Maybe..? Hard to test
- Compare with *Flatland*
  - 3D beings like us see a sphere
  - 2D beings would only see a circle
- Extra dimensions?
- Basis of String Theory
  - Unconfirmed
Wormholes

- Galaxies are >10,000 ly away
- “Traversable” wormholes by Kip Thorne 1988
- Gravitational warping of spacetime
- Connect distant points in space…
  - …or time!

57:30 – 60:30
“I think the laws of physics very probably forbid warp drives and traversable wormholes. The research that has gone on over the past 25 years trying to determine whether it’s possible all point in negative directions, but it’s not a firmly closed door…. the laws of physics probably forbid it, but, gee, if they don’t, it would be great to have!”

-Kip Thorne
The Tesseract

- 4D hypercube
- *Interstellar* renders time along a spatial dimension axis
- Cooper sees bedroom at increasing times as he moves in one direction
- Very unlikely
Time Travel?

- Bootstrap Paradox
  - “Ghost” gives Cooper NASA info
  - “Ghost” is future Cooper
  - No origin for info
- Very unlikely we need to worry
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Physics and *Interstellar*

- Thorne's guidelines:
  - “Nothing would violate established physical laws”
  - “All the wild speculations... would spring from science”
- Core elements of the story informed by established physics
- Stunning graphics led to **discoveries!**
Space Science: Present and Future

- LIGO and Gravitational Waves
  - Entirely new way to observe universe
- Evolved Laser Interferometer Space Antenna (eLISA)
  - Like LIGO, but in space
- Exploring Mars
  - NASA: It has liquid water!
  - SpaceX: Let’s colonize/nuke it!
- Asteroid Mining
You can help!

Vote to continue funding space science and exploration

or

Join the effort on the ground floor through research!
Further Reading featuring Kip Thorne

- The Science of *Interstellar* by Kip Thorne
- Visualizing *Interstellar’s Wormhole* in AIP
- Gravitational lensing by spinning black holes in astrophysics, and in the movie *Interstellar* in IOPscience
- How Building a Black Hole for *Interstellar* Led to an Amazing Scientific Discovery by Adam Rogers in WIRED
- Parsing the Science of *Interstellar with Physicist Kip Thorne* by Lee Billings in SA
Further-er Reading

- “The Science of Interstellar Explained” by Karl Tate
- “Extra Dimensions Explained” and “Gravitational Waves Explained” by PhD Comics
- *Flatland* by Edwin Abbott
- *Minute Physics* YouTube Channel
Thank you!

Questions?