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Cumulative Impacts of Oil Fields on Northern Alaskan Landscapes

D. A. Walker, P. J. Webber, E. F. Binnian, K. R. Everett, N. D. Lederer, E. A. Nordstrand, M. D. Walker

Proposed further developments on Alaska's Arctic Coastal Plain raise questions about cumulative effects on arctic tundra ecosystems of development of multiple large oil fields. Maps of historical changes to the Prudhoe Bay Oil Field show indirect impacts can lag behind planned developments by many years and the total area eventually disturbed can greatly exceed the planned area of construction. For example, in the wettest parts of the oil field (flat thaw-lake plains), flooding and thermokarst covered more than twice the area directly affected by roads and other construction activities. Protecting critical wildlife habitat is the central issue for cumulative impact analysis in northern Alaska. Comprehensive landscape planning with the use of geographic information system technology and detailed geobotanical maps can help identify and protect areas of high wildlife use.

THE DEPARTMENT OF INTERIOR HAS RECOMMENDED LEASing 1.5 million acres of the coastal plain portion of the Arctic National Wildlife Refuge (ANWR) for oil exploration (*1–3*). The recommendation was based on the nation's need for new energy resources and a perception that major ecological impacts could be avoided because of knowledge gained from experience in the Prudhoe Bay Oil Field (Fig. 1). Although many lessons were learned at Prudhoe Bay about avoidance of problems related to construction in permafrost regions and conflicts with wildlife, there are still difficult issues regarding cumulative effects of the existing and proposed oil fields.

The regulatory definition of cumulative impacts is (*4*)

> . . . The impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (Federal or non-Federal) or person undertakes such actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time.

Cumulative impacts are of particular concern in the ANWR because several oil fields may affect the wilderness and wildlife resources. A vast complex of roads, pipelines, and service centers stretching across the Arctic Coastal Plain could have unpredictable long-term impacts on the total function of the coastal plain ecosystem. The environmental impact statement process must, by law, examine cumulative impacts, but there currently are no standardized methods for doing this.

Cumulative Impacts in Arctic Wetlands

Flooding and thermokarst are important aspects of cumulative impacts in arctic wetlands. Permafrost is largely responsible for poor drainage and for thaw lakes that cover the Arctic Coastal Plain. Many of the most valuable wetlands form in drained thaw-lake basins that represent one phase in the thaw-lake cycle (*5*). These low areas are particularly susceptible to flooding caused by road and gravel-pad construction. Most buildings, oil wells, and roads in the region are constructed on thick gravel pads that rise 1.5 to 2 m above the flat tundra. This design helps prevent melting of the underlying permafrost and subsequent subsidence of the roads or buildings, but it also causes roads and gravel pads to act as dams, intercepting the natural flow of water. Where roads traverse drained thaw-lake basins, flooding is a predictable result (Fig. 2). Natural water levels, including their seasonal and year-to-year variability, are critical to maintaining the wetland diversity and function. A flooded wetland can have as large an impact on wildlife as a drained wetland because flooding alters the heterogeneous mosaic of water and

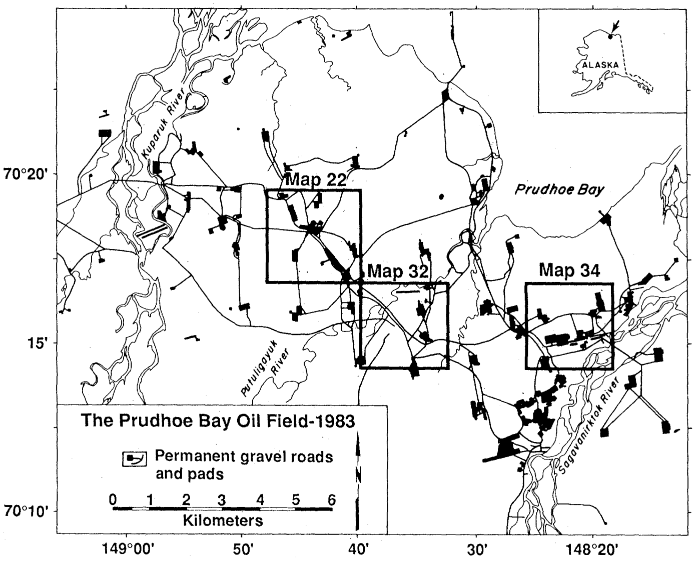

Fig. 1. Road network and facilities in the Prudhoe Bay Oil Field, 1983, with locations of the maps of the three intensive study areas used for the detailed analysis of oil-field impacts. Most of the area is part of a flat thaw-lake plain landscape unit. Maps 32 and 34 also have floodplains and terraces.

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Fig. 2. A large drained lake basin that was traversed by a road in the Prudhoe Bay Oil Field. The area farthest from the camera was flooded to about 1 to 1.5 m in depth. The foreground area is not flooded and contains many sites suitable for waterfowl nesting. Note the numerous ice-covered thaw lakes and the ice-free runoff water in the flooded lake basin. Numerous other roadside impoundments are visible along the road leading into the background. [Photo by L. Klinger, 21 June 1982]

terrestrial microsites essential for waterfowl and shorebird feeding, breeding, and nesting (*6*).

Thermokarst is a localized thawing of ground ice resulting in a surficial depression and eventual erosion (*7*). Thermokarst is involved with thaw-lake formation as a natural process (*5*), but it can also be initiated and accelerated by man's activities, and when in close proximity to buildings and roads, has the potential for destructive consequences. Such depressions often fill with water, and water's low albedo usually results in heat absorption at the site and further growth of the thermokarst feature. Thus, the process of thermokarst is difficult to stop once it has been initiated (*8*), and often it must run its course until a state of equilibrium is reestablished (*9*). Thick road berms, pilings for buildings, and elevated oil pipelines are examples of engineering designs that are used to prevent melting of ground ice. There are, however, numerous situations where it is difficult to prevent thermokarst. One example is in roadside areas where the combination of road dust, flooding, and warming effects of the road can result in thermokarst (Fig. 3) (*10, 11*). This is a common phenomenon along the older heavily traveled roads in the Prudhoe Bay Oil Field.

The Prudhoe Bay Oil Field: Experiment in Arctic Ecosystem Management

Other published analyses of cumulative impacts have stressed the importance of examining large landscapes (*12–18*) and of using long-term historical case studies (*1, 12, 16, 17*). At Prudhoe Bay, we focused on three large 22 km^2 areas where there have been major impacts. We mapped the original landscape from aerial photographs taken by the U.S. Navy in 1949, and then mapped sequential years of development from 1968 to 1983 using a series of aerial photographs taken by the oil industry. This information was entered into a geographic information system (GIS) data base consisting of layers of geobotanical information, natural disturbance, and anthropogenic disturbances (*19, 20*). The basic geobotany of the region was previously described and mapped (*21–25*).

We asked a series of specific questions regarding the history of development. What were the spatial arrangement and relative cover of natural geobotanical features (vegetation, water cover, landforms, surface forms, soils, and landscape units) before development? What were the rates of growth of the major disturbance types (for example, roads, gravel pads, and flooding)? Were the patterns of anthropogenic disturbances related to broad landscape units (flat thaw-lake plains as opposed to floodplains and terraces)? How do areas covered by direct, planned development (for example, roads and gravel pads) compare with areas covered by indirect, unplanned impacts (for example, flooding and thermokarst)? Are certain geobotanical features more frequently used than others for construction sites? Is there any evidence of synergistic impacts? [Synergistic impacts are those that have interactive reinforcement over time and are distinguished from cumulative impacts which represent a simple aggregation of impacts (*17*).] Here, we focus on the differences in impacts on the two major landscape units, (i) flat thaw-lake plains and (ii) floodplains and terraces. These units are areas of distinct similar geobotanical character and, to a large extent, define regional distribution patterns for plant and wildlife species. Flat thaw-lake plains are covered by oriented thaw lakes and drained thaw-lake basins. The areas between lakes are flat and generally wet with expanses of pond complexes and low-centered ice-wedge polygons. This unit contains drained thaw-lake wetland habitat and pingos (ice-cored hills), both of which are sites of high biotic diversity (*26–28*). The floodplains and terraces unit is associated with streams and rivers. It includes young terrace surfaces that have channel patterns and other topography typically associated with fluvial systems, and no oriented thaw lakes. This unit is particularly important in the total function of the landscape because the river systems have high floristic diversity and are movement corridors for numerous large animals such as caribou, musk-ox, grizzly bear, and wolf.

Patterns of Development

The entire oil field. The Prudhoe Bay Oil Field presently occupies about 500 km^2 between the Kuparuk and Sagavanirktok rivers. In the final year of our study (1983), there were more than 350 km of roads, 21 km^2 of tundra covered by gravel, and another 14 km^2 that had been flooded because of road and gravel-pad construction. The pace of development proceeded at a nearly constant rate throughout the first 15 years since discovery of the field in 1968 (*19*) (Fig. 4). In 1983, the growth of the road network within the relatively new Kuparuk Oil Field just west of the Prudhoe Bay field was simultaneously proceeding at a rate similar to that at Prudhoe Bay, thus doubling the total rate of new development on the North Slope (*19*).

Comparison of landscape units. Approximately 1730 hectares, 29% of the total area of maps 22, 32, and 34 (Fig. 1) had some form of disturbance by 1983. The area covered by gravel pads showed a steady increase throughout the 15-year period. New pads were built and others were enlarged to accommodate expanded camp facilities. In one instance, a pingo was removed to level the site for a gravel pad.

The patterns of disturbance within the two landscape units are distinctly different (Fig. 5). Within the flat thaw-lake plains, the rate of growth of the road network began leveling off after about 5 years. This pattern was noted previously for densely developed portions of the field (*19*).

Flooding was the most extensive impact on the flat thaw-lake

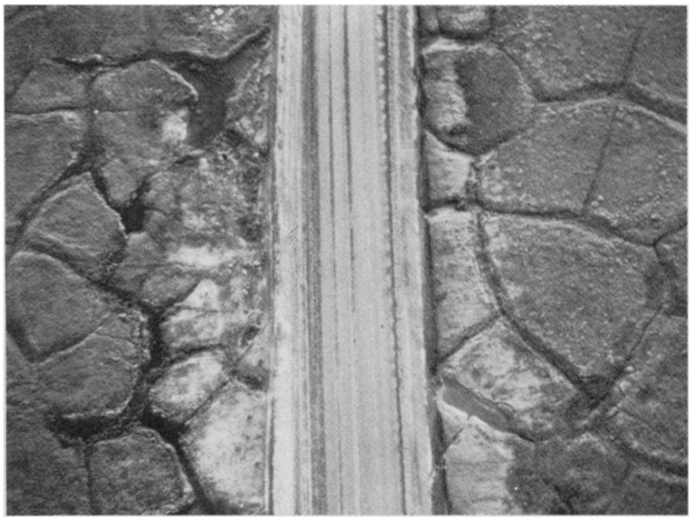

Fig. 3. Aerial view of a road passing through an area of ice-wedge polygons. The perimeters of the polygons are underlain by massive ground ice (ice wedges). Heavy dust (light-colored areas) and thermokarst (dark-colored ponds) are evident along the road margins. The ice wedges are prone to melting when the albedo of the surface is changed. The road is approximately 16 m wide, and the thermokarst and dust effects extend up to 20 m on both sides of the road.

plains, particularly in the area of map 22, where over 22% of the area in the map was flooded. The most severe flooding occurred in drained lake basins, particularly where roads and gravel pads blocked the natural drainage patterns.

Excavations were essentially absent on the flat thaw-lake plains but were a dominant component of anthropogenic disturbance within the floodplains and terraces landscape unit. When Prudhoe Bay was first being developed, the obvious gravel resources in the braided rivers were heavily exploited. In the map 32 region, gravel mining destroyed a portion of the narrow floodplain of the Putuligayuk River. In comparison, the extensive excavations on the broad, braided Sagavanirktok River floodplain had relatively minor effects on habitat along the river's margins. There was also a noticeable decline of the total area affected in the Sagavanirktok River because annual flooding helped restore natural channel patterns. The implication is that narrow floodplains are poor sites for gravel mines, and broader braided rivers may offer some sites that could be naturally restored, providing precautions were taken not to block fish or wildlife corridors. There are still major gravel mines on the rivers, but most new mines are open-pit operations on old alluvial deposits away from rivers. Such mines are a good alternative because they completely avoid conflicts with extant riparian ecosystems.

Thermokarst—a synergistic impact. Thermokarst occurs primarily on the flat thaw-lake plains. Its virtual absence on floodplains and terraces is due to low ground-ice content in these areas. The amount of thermokarst just exceeds the area covered by roads on the flat thaw-lake plains (maps 22 and 34). There is generally a delay between the construction of a road or pad and the onset of thermokarst around the feature. The thermal effects are most noticeable where there is a combination of disturbance factors such as stripping the tundra vegetation mat, accumulation of large amounts of road dust, flooding, or heating of the tundra caused by flaring operations. Thermokarst associated with construction is thus an example of a synergistic effect. Figure 5 shows low levels of thermokarst before 1977, but increasing thereafter. At present, it is unlikely that the existence of the oil field alone would lead to widespread thermal disintegration of the landscape; however, the possibility that heat generated by the field operations combined with climatic warming (*28*) could lead to more extensive thawing of ground ice cannot be ruled out.

Direct impacts compared to indirect impacts. If impacts are examined in terms of direct (roads, gravel pads, excavations) and indirect (flooding, thermokarst, construction debris, road dust) effects, there is considerable difference between landscape units. On the flat thaw-lake plains, indirect impacts exceeded direct impacts (844 compared to 560 ha). This was due largely to flooding, especially in the wettest portions of the flat thaw-lake plain. For example, in the region of map 22, which is the wettest terrain mapped, indirect impacts were more than double those of direct impacts (522 compared to 223 ha); in the floodplains and terraces, direct impacts (mostly excavations) were dominant.

Selection of well-drained terrain in wet landscapes. It is of interest to know if certain vegetation types were preferentially (perhaps unintentionally) affected by disturbance. We found that there was a selection for well-drained sites where roads and pads are often routed around wet terrain (Fig. 6). Dry and moist sites are disproportionately selected as construction sites in wet landscapes, where they are less common and are also most valuable for waterfowl and shorebirds. They are well-drained components in mosaics of wetland habitat. Such sites are usually heterogeneous

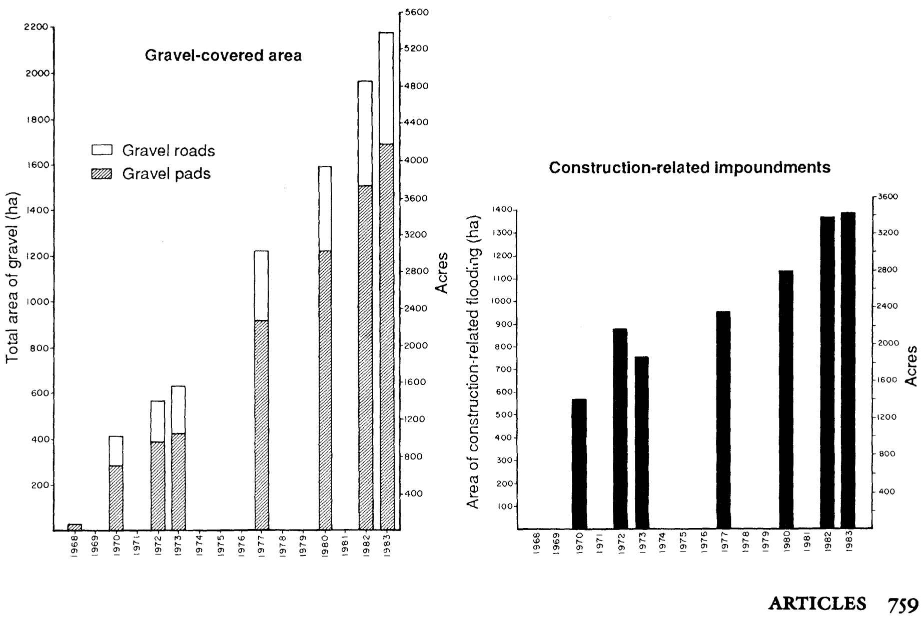

Fig. 4. Historical progression of gravel placement and flooding in the Prudhoe Bay Oil Field. Bars are shown only for years of available photography. The more irregular growth of flooding reflects yearly differences in timing of aerial photographs (early summer photos generally have more flooding), varying amounts of summer precipitation, and new culverts which drain old impoundments (*19*).

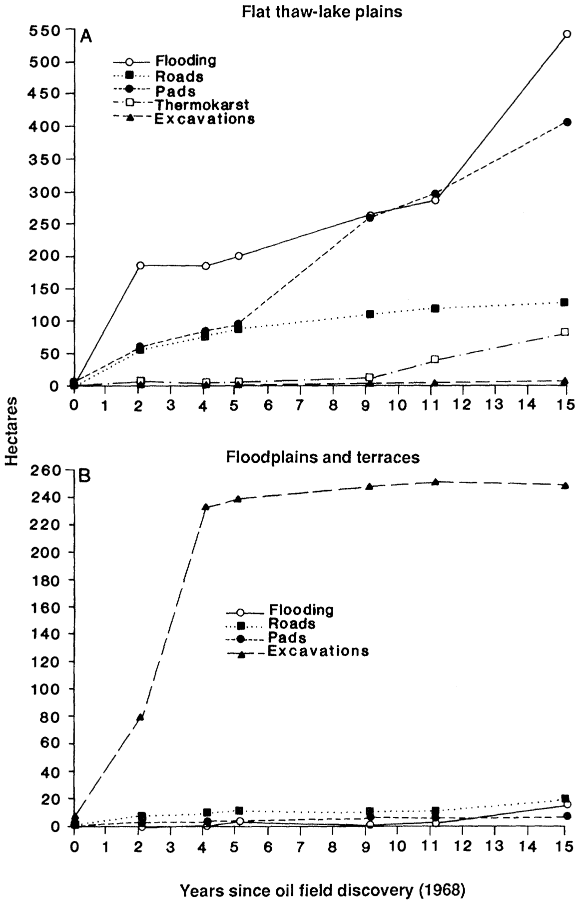

Fig. 5. Historical progression of common anthropogenic disturbances on the principal two landscape units (in maps 22, 32 and 34). (**A**) The pattern for roads follows a saturation curve for the total study area and for densely developed areas, but in less developed areas road growth continued at a steady pace throughout the period of the study. The inflection point at 5 years on the "Pads" curve reflects an oil-industry decision to increase oil-well density from one well per square mile to four wells per square mile. Flooding follows a fluctuating but steady growth and exceeds the area of any other single impact. Thermokarst shows a notable increase after 1977. (**B**) On the floodplains and terraces, excavations (gravel mines) are the primary disturbance. However, the study area did not include any drill pads on floodplains but these do occur in other parts of the oil field. Direct impacts are roads, pads, and excavations; indirect impacts include flooding and thermokarst. On the flat thaw-lake plains, indirect impacts exceed the direct impacts, whereas on the floodplains and terraces, direct impacts were dominant.

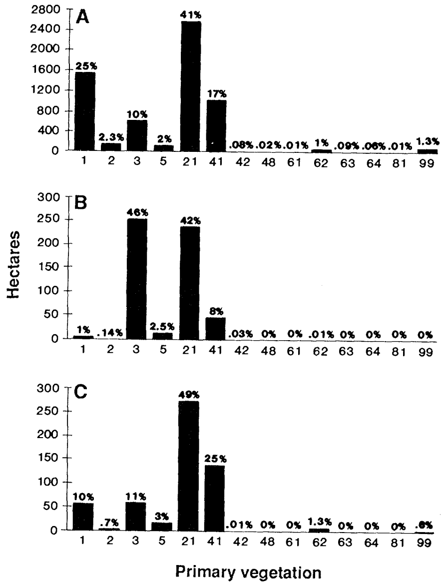

Fig. 6. Areal analysis of the three 1:6000-scale maps as of 1983. (**A**) Percentage distribution of potential natural vegetation; (**B**) percentage of each vegetation type disturbed by flooding; (**C**) percentage of each vegetation type disturbed by gravel placement. For the entire data set there was no statistically significant difference between the gravel-covered vegetation and the natural distribution of vegetation types, but on maps 22 and 32 (wetter portions of the field) there was a significant difference. The analysis excluded lakes because roads are normally routed around these. The total impact on vegetation type 3 (aquatic sedge marsh) covers over 53% of the total available area ot this stand type and suggests that this unit is particularly susceptible to indirect impacts. Vegetation legend: 1, water; 2, aquatic grass marsh; 3, aquatic sedge marsh; 5, aquatic moss marsh; 21, wet sedge tundra; 41, moist, nontussock-sedge, dwarf-shrub tundra; 42, moist, tussock-sedge, dwarf-shrub tundra; 48, moist low shrubland; 61, dry, dwarf-shrub, fruticose-lichen tundra; 62, dry, dwarf-shrub, crustose-lichen tundra; 63, dry, dwarf-shrub, forb, lichen tundra; 64, dry, dwarf-shrub, forb, grass tundra; 81, dry forb tundra; and 99, barren.

with high biotic diversity, as is the case in most complex landscapes with abundant habitat edge (*29*).

Cumulative Impact Analysis and Future Development in Northern Alaska

Before judging the effectiveness of the designs used to prevent environmental damage on the North Slope, one must consider the information that was available at the time of development. For example, how well could potential impacts from flooding or thermokarst have been predicted and avoided 15 years ago? Undoubtedly, some areas should have been avoided altogether, but damage was less predictable in other areas. We now have the benefit of the Prudhoe Bay experience, but the lessons learned in the wet landscape at Prudhoe Bay may be less relevant in better drained areas such as the Arctic National Wildlife Refuge. For example, flooding would be less of a problem in the ANWR, but other unforeseen problems could develop. More extensive thermokarst could occur in acidic tundra areas, which are susceptible to damage from alkaline road dust (*11*). [The Prudhoe Bay Oil Field is in an area of alkaline tundra, which is highly buffered against the effects of dust (*11, 23, 25*).] The highly ice-rich permafrost terrain of the hilly landscapes combined with greater topographic relief could cause additional thermokarst problems (*9*). Long-term monitoring of the Kuparuk Oil Field with the same techniques used in this study could provide useful insights for proposed development in ANWR. The more hilly terrain in the Kuparuk field is similar to that in much of the ANWR, and recent construction practices have incorporated many of the lessons learned at Prudhoe Bay.

The major points to consider from this study are the following: (i) there have been major landscape impacts caused by the Prudhoe Bay Oil Field, (ii) indirect impacts, such as thermokarst, may not develop until many years after the initial planned developments, and (iii) the total area covered by direct and indirect impacts can greatly exceed the area of the planned development. We have discussed only the impacts to the geobotanical landscape. The implications of a gradually expanding oil-field network for wetland values, wildlife corridors, calving grounds, and regional aesthetics also need to be addressed; however, the lack of baseline wildlife information at Prudhoe Bay prior to development hampers such studies. There is a need to develop methods to assess cumulative impact and to foster comprehensive regional planning to anticipate the large impacts that are likely to occur on the coastal plain in the next few years.

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Millisecond Pulsar PSR 1937+21: A Highly Stable Clock

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The stable rotation and sharp radio pulses of PSR 1937+21 make this pulsar a clock whose long-term frequency stability approaches and may exceed that of the best atomic clocks. Improvements in measurement techniques now permit pulse arrival times to be determined in 1 hour at the Arecibo radio telescope with uncertainties of about 300 nanoseconds relative to atomic time. Measurements taken approximately every 2 weeks since November 1982 yield estimates of fractional frequency stability that continue to improve with increasing averaging time. The pulsar's frequency stability is at least as good as 6×10^{-14} for averaging times longer than 4 months, and over the longest intervals the measurements appear to be limited by the stability of the reference atomic clocks. The data yield a firm upper limit of 7×10^{-36} gram per cubic centimeter for the energy density of a cosmic background of gravitational radiation at frequencies of about 0.23 cycle per year. This limit corresponds to approximately 4×10^{-7} of the density required to close the universe.

A RAPIDLY SPINNING NEUTRON STAR, BRAKED ONLY BY THE magnetic dipole radiation that gives rise to its beamed radio emission, is a potential frequency standard free from the perturbations of the solar system (*1*). Despite their impressive stabilities (*2*), the moderate rotation frequencies (ν) of most pulsars (0.5 to 5 Hz) limit the precision of timing measurements to $\gtrsim 100$ μsec, about an order of magnitude less than the precision of modern cesium clocks on time scales of a few years. Furthermore, most pulsars are young objects, no more than a few million years old; their magnetic moments are apparently decaying, and the neutron stars are still cooling and stabilizing after the catastrophic supernova explosions in which they were formed. Consequently, these "ordinary" pulsars exhibit low-level frequency instabilities $\Delta\nu/\nu \gtrsim 10^{-12}$ over time scales longer than a few years (*3*).

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